The Adequacy of Environmental Information for Outer Continental Shelf Oil and Gas Decisions: Georges Bank

Committee to Review the Outer Continental Shelf
Environmental Studies Program

Board on Environmental Studies and Toxicology

Commission on Geosciences, Environment, and Resources

National Research Council

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1991

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, NW Washington, D.C. 20418

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Support for this project was provided by the U.S. Department of the Interior, Contract No. 14-12-0001-30342.

A limited number of copies of this repro are available from the Board on Environmental Studies and Toxicology, 2101 Constitution Avenue, N.W., Washington, D.C. 20418

Printed in the United States of America

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*This study originally was undertaken under the auspices of the Commission on Physical Sciences, Mathematics, and Resources (see Appendix A).

Preface

Potentially one of the world's most productive fishing areas, Georges Bank is offshore of New England and the Canadian Maritime Provinces of New Brunswick and Nova Scotia. Proposed U.S. outer continental shelf (OCS) oil and gas activities in the Georges Bank area, including those addressed in the draft environmental impact statement for lease sale 96, have raised concerns about risks of adverse impacts on fisheries, tourism, and recreation.

In response to a request from the Minerals Management Service (MMS) of the U.S. Department of the Interior, the National Research Council (NRC) has reviewed the adequacy of available information on environmental issues and estimates of oil and gas resources for the north Atlantic area covered by lease sale 96. This report by the NRC's Committee to Review the Outer Continental Shelf Environmental Studies Program and its panels addresses the environmental issues; another NRC committee has addressed the hydrocarbon estimates. At the time of the present request, the members of the committee and its panels were reviewing the MMS Environmental Studies Program for all OCS areas. The present study extended beyond MMS's Environmental Studies Program and considered all sources of environmental information for lease sale 96, such as environmental impact statements, information developed by MMS's Branch of Environmental Modeling, and information from nongovernment sources.

In the spring of 1989, the committee and its panels were also asked by President Bush's cabinet-level Task Force on OCS Leasing and Development to review the adequacy of scientific and technical information about environmental impacts for three lease sale areas off southwestern Florida, southern California, and northern California. Because this was a presidential request and had a very tight deadline, that study took precedence over all other work and was completed in November 1989.

The committee and its panels conducted their assessments by focusing on their charges—environmental impacts and environmental studies-but they were ever mindful that these concerns are imbedded within the wider context of other environmental issues and intertwined with national energy policy, foreign policy, and economic policy. The enhanced national and international attention to these issues during the course of our deliberations because of the *Exxon Valdez* oil spill and the Iraqi invasion of Kuwait were sober reminders of this wider context.

I wish to thank the committee and panel members, especially the panel chairs—Garry Brewer, Judy McDowell Capuzzo, and Maurice Rattray, Jr.—for their dedicated hard work and intellectual contributions and for volunteering their time beyond the initial efforts requested of the committee and panels. Art Maxwell has my special thanks for serving de facto as vice chair of the committee and representing the committee at a congressional subcommittee hearing. Many people at MMS provided valuable and detailed information to assist us in our deliberations. Special thanks go to Don Aurand, Colleen Benner, William Bettenberg, Edward

Cassidy, John Goll, Walter Johnson, Carolita Kallaur, Robert La Belle, James Lane, William Lang, Harry Luton, and Bruce Weetman. Other experts provided input to our deliberations and their efforts are very much appreciated. Special thanks go to Brad Butman, Ed Cohen, Deborah French, Donald Gordon, and Patricia Hughes.

The National Research Council staff of the Board on Environmental Studies and Toxicology (BEST) devoted many months of hard work for the committee and panels. Project Director David Policansky coordinated this multidisciplinary effort and has my special thanks for his professionalism, cheerful demeanor, and thoughtful input during the many long sessions of the committee and its panels and extensive work between meetings. Sylvia Tognetti managed the complex task of providing the committee and panels with documentation and research assistance. Holly Wells provided essential and timely administrative support, and the report was edited by Roseanne Price and Norman Grossblatt. James J. Reisa, director of BEST, provided thoughtful advice to me in my role as chair of the committee. I am grateful to them all.

John W. Barrington
Chair, Committee to Review the
Outer Continental Shelf
Environmental Studies Program

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BACKGROUND

Georges Bank, a large, shallow marine bank with important fishery resources and possibly important oil and gas resources, lies east of Massachusetts in the territorial waters of both the United States and Canada. The Department of the Interior has planned since 1974 to lease parts of the north Atlantic outer continental shelf (OCS)—including part of Georges Bank—for oil and gas exploration. One sale was held in 1979, but no oil or gas was ever produced. As a result of public concern about the environmental impacts of oil and gas production on the U.S. OCS, Congress declared a moratorium on drilling on Georges Bank and an area to the southwest; the moratorium has been reauthorized annually since 1984 and is expected to last until the area's long-term leasing status is settled. To resolve some of the issues that led to the moratorium and as part of a process of fact-finding and policy discussions, the Minerals Management Service (MMS) of the Department of the Interior asked the National Research Council (NRC) in 1988 to assess the adequacy of the estimates of hydrocarbon resources and available scientific and technical information on potential environmental effects of OCS activities in the North Atlantic area covered by lease sale 96. The area covered by this lease is adjacent to the original moratorium area and includes a small part of Georges Bank. In 1988, Congress expanded the moratorium area, in effect halting the sale. In June 1990, President Bush announced a moratorium on OCS activities in several areas, including Georges Bank, to last until the year 2000.

This report-by the NRC's Committee To Review the Outer Continental Shelf Environmental Studies Program (the OCS committee) and its panels on physical oceanography, ecology, and socioeconomics—reviews the adequacy of information bearing on the potential environmental impacts of OCS oil and gas activities for the Georges Bank sale area. To carry out its charge, the OCS committee and its panels had to consider the overall OCS leasing process, and particularly the leasing decision itself; this was essential for answering the main question about the adequacy of scientific information for leasing decisions. The committee and panels' working definition of adequacy is presented in Chapter 1.

Recently, the OCS committee addressed similar issues in response to a presidential request concerning three lease sale areas off northern and southern California and southwestern Florida. A companion committee has reviewed the hydrocarbon resource estimates for those areas and the Georges Bank area. The issues addressed are similar to those in the OCS committee's California-Florida report, so the present report is organized along the same lines as the earlier report and restates or summarizes some appropriate material from it (especially in Chapter 1).

CONCLUSIONS

Many factors beyond the committee purview properly influence OCS decisions-for example, national energy policy, world events, trends in oil and gas prices; the condition of the national economy and federal budget, state laws, and industry demand. Nevertheless, s'ound scientific information remains essential to inform these decisions on the timing and location of OCS leasing and development.

The types of environmental studies and information needed to provide information for decisions on OCS oil and gas activities correspond to the different phases of activity. These phases are leasing and exploration, development and production, and decommissioning. The information requirements are discussed in three disciplinary categories: physical oceanography, ecology, and socioeconomic.

Physical Oceanography

Generalized projections of ocean currents and the potential trajectories of oil and other contaminants from OCS operational discharges constitute the minimum physical oceanographic information needed for a leasing decision. Accurate estimates of the uncertainty of predictions (error bounds) are essential. Such predictions, obtained with numerical circulation models, are used in MMS's Oil Spill Risk Assessment (OSRA) model. But, despite much study, the goal of accurate estimates of uncertainty remains elusive, because the Georges Bank area is complex and the numerical circulation models have not been properly verified against field observations. Only when such models have been derived from and tested against available field observations will it be possible to determine whether more physical oceanographic information is needed and if so, what kinds. Recent efforts by MMS to improve the descriptions of wind fields and to verify them against observations represent progress in directions recommended by this and other recent "NRC reports.

Ecology

The minimum biological information needed for a leasing decision is the distribution and abundance of important species and biotic assemblages potentially at risk. The committee concludes that the available biological information-inventories of biological resources at risk-is adequate for a leasing decision in the Georges Bank region, even though the precise risk in any specific area cannot yet be determined. After leasing, more detailed site-specific analyses would be needed during exploration. However, biological information by itself is insufficient even for a leasing decision if the available physical oceanographic information cannot permit predictions of which organisms and biological communities—if any—might be affected by OCS oil and gas activities. Thus, better physical oceanographic information about Georges Bank—or at least better verification and analysis of what exists-is needed before biological information can be successfully used.

Socioeconomics—The "Human Environment"

The OCS Lands Act as amended in 1978 requires evaluation of how the "human environment" might be affected by OCS development. (The "human environment" is defined in the statute as "the physical, social, and economic components, conditions, and factors which interactively determine the state, condition, and quality of living conditions, employment, and health of those affected, directly or indirectly, by activities occurring on the OCS. . ."), Although much socioeconomic information on New England is available, it cannot be used to detect changes that might occur as a result of OCS activities, because most of it was not gathered specifically to assess OCS impacts and is out of date. Moreover, much of the information on New England in various documents has not been analyzed or coherently synthesized in the draft environmental impact statement (DEIS) for lease sale 96 or in other documents, so it does not provide an adequate basis for a leasing decision.

Future Activities

The process of scientific discovery is not predictable, so the amounts of time and money required to get the information needed for a leasing decision cannot be known precisely in advance. But the committee judges that the task could be substantially accomplished within several years, with only a modest increase or reallocation in the budget of the Environmental Studies Program. The information thus obtained would permit a decision on whether to proceed with the exploratory drilling recommended by the companion NRC Committee on Undiscovered Oil and Gas Resources to improve the estimates of hydrocarbon resources in the Georges Bank area. Substantial additional ecological, socioeconomic, and physical oceanographic information bearing on potential environmental impacts would be needed for decisions about development and production in the lease sale area.

A congressional moratorium stopped the leasing process some time ago. In the present review, this committee relied primarily on the DEIS for sale 96 (publication date February 1988) as a description of the scientific and technical information used by DOI. It also reviewed some documents that were available up to mid-1990. The committee expects that more up-to-date information and analysis will be provided in new decision documents if the leasing process is restarted.

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Introduction

The oil spill off Santa Barbara, California, in 1969 led to an increased awareness of environmental issues among the public in the early 1970s. The *Exxon Valdez* spill has had much the same effect recently. This heightened awareness of the importance of wise management of our natural resources has challenged decision makers who must balance the need to develop certain natural resources against the need to protect certain others. One area in which this heightened awareness has led to a great potential for conflict is in the development of outer continental shelf (OCS) oil and gas and the associated environmental concerns.

The environmental issues surrounding OCS oil and gas development have led Congress and the President to impose moratoria on leasing in several OCS areas, including the north Atlantic. The congressional moratorium on Georges Bank was declared in 1984; it has been reauthorized annually since then and is expected to last until the area's long-term leasing status is resolved. The area covered by the Department of the Interior's lease sale 96 is adjacent to the moratorium area and includes a small part of Georges Bank. In 1988, Congress expanded the moratorium area, in effect halting the sale and prelease activities. In June 1990, President Bush announced a moratorium on OCS activities in several areas, including Georges Bank, to last until the year 2000. In the present review, this committee relied primarily on the DEIS for sale 96 (publication date February 1988) as a description of the scientific and technical information used by DOI. It also reviewed some other documents that were available up to mid-1990. The committee expects that more up-to-date information and analysis will be provided in new decision documents if the leasing process is restarted.

The National Research Council (NRC) has addressed environmental issues surrounding OCS oil and gas development in the past. In 1973, President Nixon asked the *Council* on Environmental Quality and the NRC to review OCS environmental concerns (NRC, 1974). Again, in 1978, the NRC issued a review of the OCS Environmental Studies Program (ESP; then run by the Bureau of Land Management) (NRC, 1978); in 1983, it issued a report on drilling discharges (muds and cuttings) (NRC, 1983); in 1985, it released its report, *Oil in the Sea: Inputs, Fates, and Effects* (NRC, 1985); and in 1989, it released *Using Oil Spill Dispersants on the Sea* (NRC, 1989c).

Most recently in response to a presidential request, the authoring committee of the present report-the NRC's Committee to Review the Outer Continental Shelf Environmental Studies Program (the OCS committee)—reviewed the adequacy of scientific and technical information on potential environmental effects of OCS activities for three lease sale areas off northern and southern California and southwestern Florida (NRC, 1989a), At the same time, the NRC's Committee on Undiscovered Oil and Gas Resources (the resource committee) reviewed the adequacy of scientific and technical information on estimated hydrocarbon resources for those three areas (NRC, 1989b).

The two committees were also asked by the Minerals Management Service (MMS) in 1988 to assess the adequacy of scientific and technical information about the environmental concerns and petroleum resources for Georges Bank. - This report, delayed by the need to comply with the presidents request, is the assessment made by the OCS committee for lease sale 96 (also called the Georges Bank lease sale because it includes areas of Georges Bank). The report of the resource committee is available as a separate document (NRC, 1990a).

At the same time that these assessments were requested, the two committees were already involved in or planning relevant studies. The OCS committee was engaged in a major review of MMS's ESP and the resource committee was being established to review methods of estimating onshore and offshore undiscovered oil and gas. These reviews of lease sale 96 were made on the basis of the committees' experience with these nationwide reviews.

In its nationwide review already in progress, the OCS committee had formed three panels to review physical oceanography, ecology, and socioeconomic, Reports from each of the panels address generic issues for all OCS lease areas nationwide, as well as critical issues for some individual lease areas. The physical oceanography report was published in mid-1990 (NRC 1990b); the other two will be published in 1991.

GEORGES BANK

Georges Bank is a large and shallow submarine bank located on the outer continental shelf along the southern side of the Gulf of Maine; it is in the territorial waters of both the United States and Canada. Its fisheries resources and perhaps its oil and gas resources are economically important to both countries. The densest populations of scallops, lobsters, and haddock are on the Canadian side of the Hague Line, the international boundary since 1986. Oil. and gas exploration has been proposed for both sides of the boundary and some has occurred. Although MMS has jurisdiction only over lease tracts in U.S. waters, scientific investigations of Georges Bank are not limited by territorial boundaries. OCS activities in U.S. waters could affect Canada, and Canadian activities could affect the United States. Therefore, international collaboration is needed to ensure adequate protection of resources.

Georges Bank is one of the most productive banks in the north Atlantic (O'Reilly and Busch, 1984) and, before it was overfished, supported one of the world's most important harvests of fish and shellfish. Most of the bank has water depths less than 100 m and some areas are as shallow as 3 m. The sides of the bank are generally steep, except at the southwest corner, and there are several submarine canyons along the southern slope. Sediment substrates on Georges Bank consist primarily of sand and gravel, with finer sediments transported off the bank by tidal currents and waves. Submarine canyons and the continental slope maybe potential sinks for fine sediment (DFO, 1988). In addition to its topographical complexity, Georges Bank is also characterized by very large high tides. Thus, it has long been of interest to physical oceanographers and ecologists.

STANDARDS OF THE OCS LANDS ACT AND AMENDMENTS

Although the primary focus of this report is on scientific rather than legal adequacy, the statutory basis for the matters being reviewed is obviously relevant to identifying the goals and assessing the adequacy of the available information. The primary statutory authority for OCS oil and gas leasing and production is the OCS Lands Act as amended in 1978 to make major program changes (OCSLA)[1]. The OCSLA requires that decisions at all stages of the leasing and development process take into account the potential impacts on the environment and attempt to balance two broad, often conflicting goals:

- to make available, the marine mineral resources of the OCS for expeditious and orderly development to meet the nation's energy demands and, at the same tune,
- to provide protection of the human, marine, and coastal environments during development and production of marine mineral resources.

In addition to these broad goals, required by the OCSLA, the present OCS leasing program, as established by Section 18 of the OCSLA (43 U.S.C. 51344), calls for a schedule of proposed lease sales, which the Secretary of the Interior must determine "will best meet national energy needs for a five year period following its approval." The timing and location of lease sales must "to the maximum extent practicable" strike a balance between the potential for oil and gas production and the potential for environmental damage and adverse coastal impact (OCSLA, Section 18,43 U.S.C. 51344(3)).

The National Environmental Policy Act of 1969 (NEPA) requires an environmental impact statement (EIS) to be prepared for all major federal actions significantly affecting the quality of the human environment. NEPA and the implementing regulations of the Council on Environmental Quality (CEQ) describe the types of information and analysis that should be included in an EIS. Extensive case law and agency guidelines have refined the information to be used by the Department of the Interior (DOI) in EISs.

In 1978, Congress took another step in defining environmental information requirements, adding Section 20 to the OCSLA (43 U.S.C. $1346) specifying requirements for environmental studies to help guide OCS leasing and management decisions. In addition to outlining general procedures, Section 20 specifies the types of environmental studies that must be conducted and how they should be used:

- Each OCS area or region is to be studied to establish the environmental information needed for assessment and management of environmental impacts-including those to the "human environment"—resulting from oil and gas development.
- This information must be used in decisions concerning postlease operations, management, and leasing.
- Studies must predict impacts on marine biota and on affected onshore and coastal areas from chronic low-level pollution, large spills, drilling muds and cuttings, and pipeline construction and on affected onshore and coastal areas from offshore development.
- Postlease monitoring and studies are required to identify thanges and trends in the environment. Monitoring of the human environment is specifically incluled in this requirement.
- An annual report to Congress on cumulative impacts is required.

Congress in 1978 also established a new standard for the approval of exploration plans, as well as development and production plans, for all OCS oil and gas areas other than in the Gulf of *Mexico*. Before this time, such plans were typically low-visibility documents, but with the

[1] See Glossary in Appendix B.

addition of Section 25 to the OCSLA (43 U.S.C. $1451), Congress added requirements for environmental findings in approving such plans and for preparation of an environmental impact statement for development and production plans at least once in each frontier area.

A high degree of intergovernmental coordination is required. First, both the exploration plans and the development and production plans are subject to a consistency certification by affected state governments under the 1972 Coastal Zone Management Act. Second, at this stage local governments play a significant role as well. MMS cart approve platform locations and operations, pipeline corridors, and offshore support, but the responsibility for siting and approving onshore facilities, which are part of the operations, falls on state and local governments. The OCSLA requires the secretary to carry out his duties under Section 20 in cooperation with the affected states. He is authorized to use information from other federal agencies "in lieu of directly conducting such activities." The act also directs the secretary to use the capabilities of the Department of Commerce to "the maximum extent possible." He may use information from any other source *(43* U.S.C. $1346(3)(c)).

ADEQUACY

The committee's operational definition of "adequacy" for scientific information has two aspects: completeness and scientific quality,

Completeness

The body of scientific information continually grows through research and discovery. Recognizing this continuing process, the committee criteria for completeness require appropriate breadth and depth of basic scientific information in all relevant disciplines needed to understand the environmental risks associated with OCS decisions. Criteria for completeness within disciplines for the north Atlantic lease sale area are described in the three chapters that deal with physical oceanography, ecology, and socioeconomic.

Scientific Quality

The standards of scientific quality entail repeatability, reliability, and validity of measurements and analyses, including appropriateness of methods and subject. The working definition of scientific quality used by the committee and panels was whether the methods described represent the current state of good practice in each scientific field—i.e., whether they would be likely to pass peer review. That does not imply that the criterion is actual publication in a peer-reviewed scientific journal, but rather that the quality of the data and scientific interpretations used for OCS decisions should meet this basic scientific standard.

Application of the Standard of Adequacy

Although adequacy, or how much science is enough, can be defined for scientific purposes as outlined above, the committee notes. that decisions must be related to scientific uncertainty in assessing risks and in making predictions. How much uncertainty is acceptable is related to the state of the science, the perceived value of the resource or activity being considered, the nature of the risk, and public concern. The issue is how to balance the need to reduce uncertainty against the increased costs in time and money of doing the science required.

The committee believes that deciding how much science is sufficient for OCS decision making should be a process whereby scientific knowledge provides an assessment of potential impacts and risks to decision makers-including the range of uncertainty-associated with environmental issues.

The definition of adequacy, and the specifics of adequacy in the case of Georges Bank that are articulated in this report, do not address an ideal but rather a minimum standard of scientific adequacy essential and appropriate to decisions with respect to this sale area. In other OCS sale areas, a description of adequate environmental information from a scientific standpoint is not absolute, but it can be produced through a process involving the federal program staff and broad-based advice from the relevant scientific communities. Risk assessment, predictability, and political considerations must then be applied against this information to decide whether the science is adequate.

The committee has evaluated only the adequacy of the scientific information as it provides the basis for informed decisions. It was not charged with evaluating the actual impacts of OCS oil and gas activities and has not done so in this report. The biological effects of specific OCS activities, such as the discharge of drilling fluids and accidental oil spills, as well as the long-term effects of oil and gas development, have been reviewed extensively by previous groups (NRC, 1983, 1985, 1989c; Boesch and Rabalais, 1987).

SOME UNDERLYING CONCERNS

Other Activities in the OCS

OCS oil and gas activities are only a portion of all human activities in the coastal and continental shelf areas (e.g., commercial fishing, shipping, recreational boating, sewage discharges) that can have adverse impacts on living resources and people. These uses create other demands on the ocean resources that can conflict with oil and gas development and also have environmental impacts on the oceans. For example, OCS oil and gas activities are only one of many sources of petroleum input to the marine environment. These activities account for an estimated 0.05 million metric tons per year worldwide of the estimated total input of 3.2 million metric tons per year, about 1.6 percent (NRC, 1985). Thus, although the committee has not evaluated the impacts of OCS oil and gas activities relative to those of other human activities in the OCS, it is clear that oil and gas activities must be viewed in perspective when assessing absolute and relative environmental risks.

Environmental Assessment: Distinction Between the Leasing/Exploration Phase and the Development/Production Phase

Another of the committee% generic underlying concerns involved the phasing of OCS leasing, exploration, development, and production. ESP studies and the assessments found in DOI's EISS have focused almost entirely on the lease sale stage. Two fundamental problems relate to this practice. First, because the exact location of oil and gas reservoirs is unknown before areas are offered for lease, it is impossible to identify the specific future location of facilities, to collect and analyze the environmental data, and to predict specific environmental impacts of development and production. Furthermore, the uncertainty about actual oil and gas reserves before exploration makes it difficult to balance the national benefits of production against the environmental risks. Second, by the time commercially viable reservoirs are identified, the industrial lessee typically has committed substantial amounts of money to acquisition and exploration of the lease and expects to proceed to development and production.

The problems arise substantially because DOI has never implemented the procedures provided in the OCSLA for lease cancellation. The procedures are time-consuming and potentially extremely costly to the government. As a result, a decision to lease is generally perceived as tantamount to a decision to develop and produce, provided that commercial reserves are found in a lease area through exploration. The point about noncancellation of leases has been made in prior studies and was considered in depth by Congress in the deliberations leading to the 1978 amendments to the OCSLA. Although some tracts are deleted from lease areas for environmental and other reasons before the sale, and development and production are subject to substantial environmental regulations and stipulations, it is in practice not possible to do adequate assessment of development and production impacts before leasing, as DOI's EISS point out. However, once it does become possible to generate the needed information an-d analysis, a decision not to proceed with development has already been effectively precluded.

The perception is widespread that leasing implies development and production if commercial quantities of hydrocarbon resources are found. [n a 1984 Supreme Court decision (*Secretary of the Interior v. California*, 104 S. Ct. 656), the majority wrote: ". . . a lease sale is a crucial step. Large sums of money change hands, and the sale may therefore generate momentum that makes eventual exploration, development, and production inevitable." The minority wrote: "Approval for exploration and development by the lessee is obviously the expected and intended result of leasing, if it were not, the Secretary would not bother to lease and the lessees would not bother to bid." In spite of provisions for a "focusing of analysis and review [that] will occur at later stages in lease sale planning , . . most states doubt that adequate analysis will be performed, and that decision alternatives will be preserved through the process" (Hershman et al., 1988). As an example, in reviewing consistency with the provisions of the Coastal Zone Management Act of 1972 for proposed north Atlantic lease sale 52, Massachusetts Secretary for Environmental Affairs James Hoyte wrote: "Exploration, development, and production activities are likely to flow from the lease sale . . ." (Hoyte, 1983). Many other local, state, and federal government officials have expressed similar points of view to the OCS committee and panels. Furthermore, several MMS officials have informed the committee that of the many OCS development and production plans submitted by industry "since 1978, none has ever been denied by DOI, although significant modifications to reduce impacts on natural resources and human habitation have been required. For these reasons, the committee and panels cannot confirm that there is a de facto separation of OCS leasing from development and production decisions in current practice.

In requiring development and production plans (except in the Gulf of Mexico, where the OCSLA does not require them), the OCSLA recognizes the distinction between environmental impacts at the exploration versus the development and production stages. The OCSLA requires that an EIS be prepared for at least one development and production plan in each OCS planning area except in the Gulf of Mexico. This requirement has resulted in detailed EISS and extensive public debate over development plans in the Santa Maria Basin and Santa Barbara Channel of California. Presumably similar analysis and dialogue will take place as other new "frontier areas" (i.e., areas that do not yet have producing wells) are opened. Nevertheless, early experience leads to the perception that the "no development" scenario is effectively precluded after leasing. This perception has affected the tone of the debate.

The committee believes that until this problem is resolved, effective environmental assessment and a credible public dialogue will be difficult. An EIS at the development and production stage could take advantage of improved knowledge and additional studies to gain information. For example, exploratory drilling to improve estimates of hydrocarbon resources, as recommended by the NRC's Committee on Undiscovered Oil and Gas Resources (NRC, 1990a) should provide some additional information. The committee recognizes that such a change in procedure could imply important changes in how industry and the federal government treat lease sale bids, revenues from bids and royalties, and associated economic issues. Nevertheless, the current delays in timely and orderly leasing decisions caused by environmental concerns might be reduced significantly by changes in current leasing procedures.

National Energy Policy

A third underlying issue of concern to the committee involved the present uncertainties as to national (federal) energy policy. In the largest sense, the leasing of federal offshore petroleum resources represents an assertion of national objectives (energy policy and the management of federal resources) in a context with high potential for conflict. This potential has obviously been realized in conflicts between the federal OCS and environmental interests, states, local governments, and other governmental jurisdictions. All these groups have raised many concerns about environmental quality, other uses of the ocean and coast, and the avoidance of undue socioeconomic impacts.

Adequate scientific information is clearly a key element in the effort to resolve these conflicts. However, the committee also is keenly aware of the demand for offshore energy and the federal revenues derived from offshore leasing. Federal energy-development objectives appear to drive MMS's program, largely determining the planned pace of leasing and the perceived need for MMS to meet program goals. There is concern that these objectives, however legitimate, are not adequately defined or placed in context by national energy policy.

2

Physical Oceanography

OVERVIEW

Predicting the movement and concentration of material released into the ocean requires knowledge of the source of the material (e.g., oil, gas, or routine discharge), the composition of the material, the rate and time of its release, and an estimate of the rate of transport by wind and ocean. It is also necessary to know how likely it is that the rate of flow of material into the sediments and the atmosphere at a particular point and time will exceed some given value.

A large number of observational studies of the physical oceanography in the Georges Bank region, sponsored by MMS and its predecessor as well as other agencies, have been conducted. These studies have yielded a considerable data base for the distribution, exchange, and mixing of water. masses and materials in the water. However, the ocean circulation model used in MMS's Oil Spill Risk Assessment (OSRA) model does not include many components of the flow field that are known to be important, and the predicted trajectories have not been demonstrated to represent adequately observed drifters. Therefore, this circulation model is unsatisfactory for use in impact assessment. Increased synthesis and use of existing information in model sensitivity studies are needed to determine the degree to which aspects of the circulation are insufficiently known or understood and to decide whether current information is adequate for OCS decision making. The specifics of the panel's conclusions and recommendations are set forth below:

1. The results from the numerical model of the circulation data used for input to the OSRA model are demonstrably inconsistent with the known circulation obtained from field observations. In this case the available field observations are to be believed, and the corresponding numerical model results are erroneous. Some reasons for the lack of agreement between numerical model results and observations can be identified, whereas others cannot with certainty.

2. The need is for a circulation model, based on observations and numerical modeling, that can reproduce the statistics of the observations (particularly Lagrangian trajectories and dispersion of oil or its surrogates) within specified error bounds. It is recommended also that a circulation model be developed that can predict, to known error bounds, the probability distribution of trajectories for the high-impact but low-probability events. In addition, simulations of several worst-case scenarios should be performed to give the policy maker some sense of the upper-bound impacts. MMS should indicate the degree of uncertainty in its

predictions. For its own planning MMS should determine how much effort would be needed to reduce uncertainty by specified amounts.

3. To use numerical models for the above purposes, it is necessary to determine their sensitivity to the parameterization of the important physical processes, to the choice of numerical techniques, and to the boundary and initial conditions. These sensitivity studies will identify data gaps that need to be filled so that the performance and sensitivity of the numerical model can be determined. The sensitivity determination can be a complex undertaking because there are an unusual number of relevant physical processes acting in the Georges Bank area, and their interaction will not be easy to unscramble. It is therefore necessary that, as an intermediate step, a numerical model be tested for its adequacy in reproducing the separate effect of each of the processes that has been determined to be important in meeting the above-stated objectives. Once the required sensitivities are known, the selection of appropriate parameterizations, numerical techniques, and boundary and initial conditions, required for the numerical model in order to achieve the specified error bounds, can be made.

4. Because of the nonlinearity of the governing equations, numerical models in principle have limitations on their abilities to predict trajectories and trajectory statistics. This imposes a further requirement, beyond those given in item 3 above, for data both as independent estimators of trajectory statistics and as verification for the numerical modeling,

5. The use of zoned transition probability matrices to describe the wind fields is inadequate as applied by MMS because these matrices do not accurately account for the temporal and spatial structure of the meteorological forcing fields. Verified limited area meteorological models or more sophisticated data-based procedures that incorporate appropriate spatial or temporal correlations should be employed. Recent efforts by MMS to improve the descriptions of wind fields and to verify them against observations (Herring and Rubenstein, 1990) represent progress in 'directions recommended by this and other recent NRC reports.

Improvements such as these in the models will lead to results, including, validation and verification, that will make it possible to assess the adequacy of existing observational information of Georges Bank.

THE PHYSICAL SETTING

Georges Bank and surroundings (see Fig. 1) are geomorphologically unique within the continental United States. The adjacent continental shelf, lying between the Gulf of Maine and the Atlantic Ocean, contains shallow banks that are separated by deeper channels leading into the Gulf. As a consequence, the physical oceanographic regime is marked by a combination of strong tidal currents, with all their associated effects, and of relatively short horizontal length scales associated with the local bathymetry. The bathymetric variability results in increased topographic steering of local currents. Furthermore, the response to wind events is considerably different from that for a typical shelf because of the presence of the Gulf of Maine. In addition, unlike the situation in Pacific and Alaskan shelf waters, the adjacent deep ocean causes changes in the shelf circulation because of warm-core rings from the Gulf Stream that frequently move onto the shelf. As a consequence of these factors, an equivalent determination of the Lagrangian trajectory for any introduced substance on this shelf is more complex than it is for other OCS sites. The following section is based on the recent review of MMS's environmental studies in physical oceanography (NRC, 1990b).

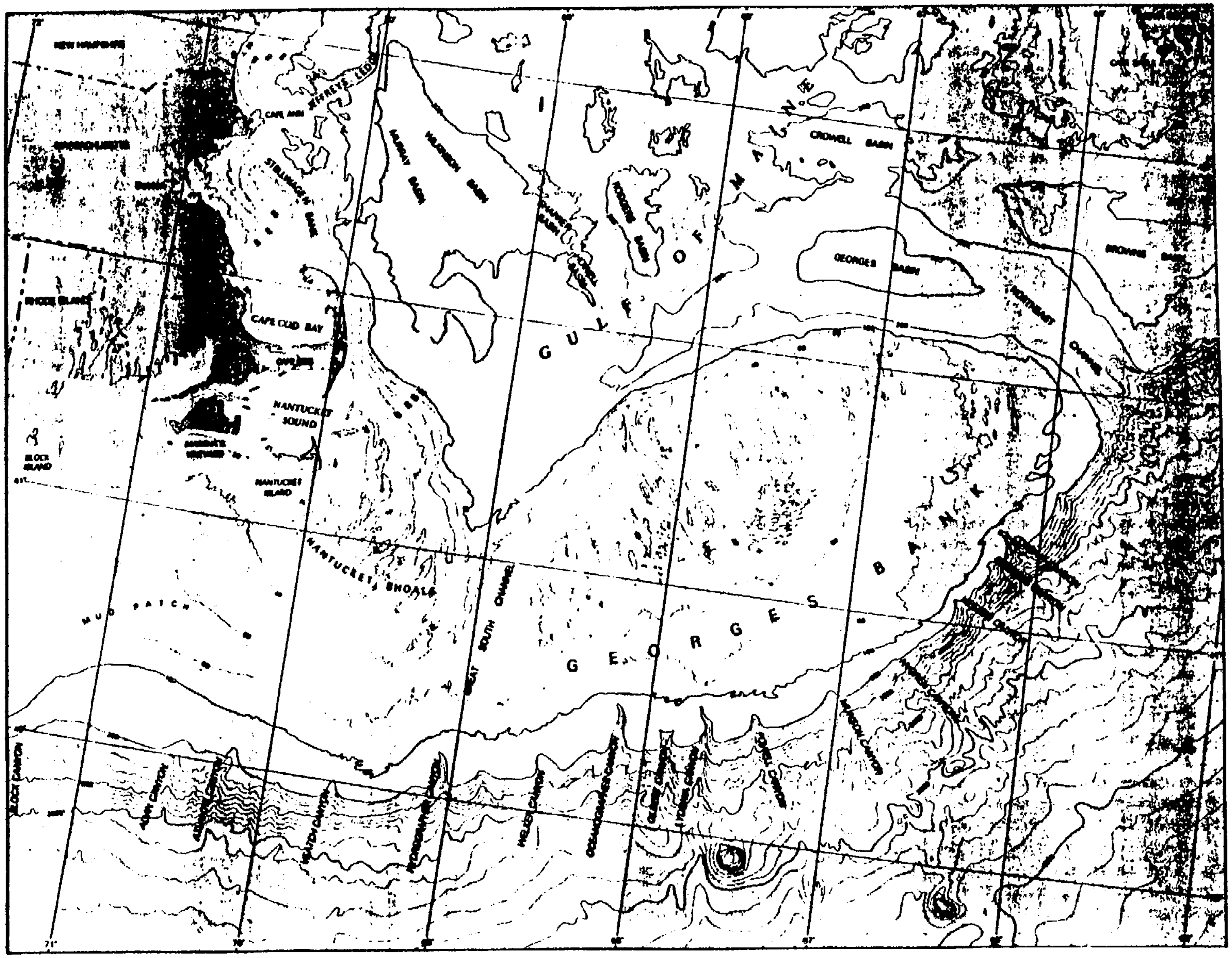

FIGURE 1 **Georges** Bank **(scale 1:2** million). **Source: Backus,** 1987a. © 1987 by the Massachusetts Institute of Technology. Used by permission.

A FRAMEWORK FOR EVALUATING IMPACTS

The Problem from a Physical Oceanographic Perspective

Before a discussion of the state of knowledge of the physical oceanography of Georges Bank and the adequacy of this information for impact assessments of oil and gas exploration or production, it is appropriate to consider the specific physical information that is needed. The problem of predicting the movement and concentration of material released into the ocean can be formally stated as follows: Given a source of some material (e.g., oil, gas, or routine discharge) as a function of space and time (x, y, z, t), what is the probability that the material's concentration at a particular spatial point (x', y', z') and time (t') will be greater than some specified value (C')? In addition, it is necessary to know the probability of the flux of material into the sediments at a particular point and time exceeding some given value, and likewise the flux into the atmosphere.

The primary physical oceanographic processes that must be considered in this problem are the following (Eckart, 1948):

1. Advection or transport: These terms refer to flows that move patches of material around but do not significantly distort or dilute them.
2. Stirring This is the process whereby flows with strong shear and strain fields on the scale of the patch size generate "streakiness," with material from the patch drawn out in tendrils into unpolluted water and streaks of water intruding into the patch. But, by itself, stirring does not alter concentrations, although it affects the probability of finding material at a particular point.
3. Mixing This process is responsible for the decrease in concentration of material. At the 'most fundamental level, mixing is accomplished by molecular diffusion intermingling the water and chemical molecules. However, molecular mixing is usually coupled with stirring to produce turbulent mixing, wherein stirring produces concentration gradients on small scales where molecular mixing can efficiently erase them. As discussed below, estimates of turbulent mixing rates depend very strongly on the scales of interest.

Collectively, we refer to 'these three processes as "exchange." It should be noted that both horizontal and vertical exchange must be considered, because, for flow fields with a complex spatial structure, exchange in a particular plane can be dependent on velocities in the orthogonal direction.

In addition, the density of the material and biological and chemical processes can play roles in the probability problem stated above. The material's buoyancy, if different from that of the ambient seawater, can result in transport and mixing at rates that differ from those of water parcels (e.g., sinking, accumulation in surface convergence zones, and differential wind drifts). ' Biological and chemical processes can produce effective sources and sinks of particular materials and introduce additional exchange mechanisms (e.g., adsorption to sinking particles).

Transport Processes in the Water Column

The fate of biological, chemical, and sediment ary constituents in the coastal zone is determined by transport processes and the mechanical and chemical properties of the various constituents. Coastal circulation, and the attendant variability in physical parameters characterizing the coastal ocean, result from complex interactions between these processes over a very broad range of time scales, from interannual periods to surface gravity wave periods of a few seconds. As a consequence of this breadth of the spectrum of motions, describing the circulation is both challenging and expensive.

Oil and pollutants are carried from one place to another by a broad spectrum of currents. But surface spills are also moved relative to the water by the wind. Waves break up and mechanically modify surface spills and drive the modified material below the surface, where it drifts with subsurface currents—sometimes to reappear later at the surface under calmer conditions. Both products from surface spills and effluents from drilling operations or from subsurface leaks (from pipelines or blowouts) may ultimately end up in bottom sediments, possibly accumulating to unacceptably high concentrations in localized regions. They may even be transported from place to place within the sediments themselves over long periods. All of these processes are of potential importance in estimating the fate of spilled or leaked material. This chapter addresses primarily the scientific knowledge necessary to take into account the first process, advection by currents.

Sediment Transport Processes

The physical processes responsible for the deposition, mixing, resuspension, and transport of bottom sediments are closely tied to the long-term effects of petroleum exploration, development, and production. Toxic by-products of drilling activities and oil spills eventually pass to the bottom by adsorption to fine suspended particulate or incorporation into detrital materials, which settle out to the bottom during periods of deposition (e.g., NRC, 1985; U.S. DOI, 1988a). The subsequent fate of the particulate and the associated toxics is then largely determined by patterns of physical mixing, resuspension, and transport. Vertical mixing and resuspension of surface sediments tend to disperse initially high concentrations of contaminants and to increase chemical interactions between particulate and dissolved phases (e.g., Bothner et al., 1987). Horizontal transport often leads to further dispersal and lower contaminant concentrations (NRC, 1983), but it may also lead to the physical concentration of contaminated particulate material in depositional environments. Toxics in the bottom sediments, pore waters, and material suspended just above the bottom may then enter the benthic food web, depending on the bioavailability of the material to the local benthic community (Boesch et al., 1987; Howarth, 1987; Neff, 1987).

Sedimentary accumulation and subsequent release of toxics may prolong the impact of a spill or discharge long past the initial occurrence. Boesch et al. (1987) have defined long-term effects to include both effects that persist for a long time as a result of some brief activity and effects that result from low-level, chronic exposure over a long period of time. Examples of the former include oiling of sediments and/or sedimentary accumulation of undegraded hydrocarbons in the aftermath of an oil spill and the impact of drilling muds and cuttings from exploratory drilling. Examples of the latter include chronic releases of oil during production, and repeated discharges of drilling muds and cuttings during development. In all cases, impacts are likely to be worse in shallow-water, depositional environments (Boesch et al., 1987; Howarth, 1987). The effects of chronic discharges on the deeper depositional environments of the OCS are still largely unknown, however (NRC, 1983; Boesch et al., 1987; DFO, 1988; Neff, 1987), because of the lack of study and the difficulty of separating long-term effects from natural environmental variability.

Space and Time Scales

oceanic flows have energy at many different space and time scales. Physical oceanographers often discuss motions in different frequency bands separately, as is done below. Although such differentiation is convenient for organizing information and understanding the mechanisms involved, one must be careful about superimposing different frequency bands to obtain the total flow field.

Although the Fourier "decomposition of a current meter record can be recombined to give the flow versus time, band-pass-filtered records of currents and pressure (for example) will not satisfy the Navier-Stokes equations when there are significant nonlinearities in the flow. The problem becomes even more severe when looking at the movement of particles in the flow-the Lagrangian description of the motion—because the evolution equation for particle position involves a nonlinear function (the flow velocity) of the position. Simple Eulerian flow fields varying in time and space with a single frequency and wavenumber give particle motions with a complex spectrum, containing both harmonics and a zero-frequency component. The latter corresponds to a net drift rate for a particle-a Lagrangian mean flow-that is different from the average velocity measured at a point—the Eulerian mean. The difference is called the Stokes velocity (e.g., Longuet-Higgins, 1969). Flows only slightly more complex can lead to chaotic particle trajectories and efficient turbulent mixing (e.g., Zimmerman, 1986). When the Eulerian flows have a broad frequency spectrum, the Lagrangian motions become even more complex and can have a spectrum quite different from the Eulerian one. The probability of a particle's entering a particular volume of space can depend upon the flows in all parts of the Eulerian spectrum; of particular concern are those bands in frequency and wavenumber space that are not resolved by a given model. These points are particularly relevant to Georges Bank because the flow field in this area has significant temporal variability in several frequency bands (tides, storms, Gulf Stream rings, seasons) and has substantial spatial structure (largely imposed by topography) on the scales of the particle excursions associated with the current fluctuations.

The dependence of stirring and mixing on the complex relationship between the Lagrangian and Eulerian spectra implies that turbulent mixing is very scale-dependent: the inferred rate of mixing depends strongly on the range of scales that are resolved. In addition, turbulent diffusion processes do not always transport material at a rate proportional to the larger-scale gradient, nor is the flux vector necessarily parallel to the mean gradient. Although it is almost universal practice to model subgrid-scale exchange processes as a kind of diffusion, it may be .inappropriate, especially in a region such as Georges Bank with strong and variable topography and density fronts.

Forcing Mechanisms

Predictive capability is usually premised on the identification and understanding of the mechanisms that couple response to forcing. The preceding section illustrates that the coastal ocean is subjected to forcing over a broad range of periods, ranging from interannual variations in the coupled ocean-atmosphere system to the atmospheric forcing responsible for the generation of surface gravity waves. Some forcing mechanisms are better understood than others: the forcing imposed by the barotropic tide on the continental margins is probably the best-understood forcing mechanism, and the influence of adjacent deep ocean currents and eddies may be the least-understood forcing mechanism. Each mechanism or process responsible for forcing the coastal ocean is modulated as a function of space and time. Predicting coastal circulation and/or its statistics thus entails a knowledge of at least the amplitude and variation of the processes that drive the coastal ocean.

Oil-Spill and Circulation Models

The above points regarding the kinematics of mixing and transport have important implications for the models used in oil-spill risk analysis. Generally, the models resolve only a limited set of scales, often just the seasonal mean circulation. In the absence of most of the temporally and spatially varying part of the spectrum, the predicted Lagrangian motion may miss many aspects contributing to drift, especially on the shorter time scales. This problem plagues all modeling efforts to some extent, but it is of particular concern for Georges Bank, where the variable flows are so strong and the length scales are particularly short.

In addition, the OSRA model used by MMS deals only with inert surface-layer material, although MMS has sponsored some work involving simultaneous calculation of the "fates" of the oil-a prediction of some of the chemical and physical changes in the hydrocarbons. The panel's physical oceanographic review focuses primarily on the prediction of exchange of passive materials; the processes discussed are generally important to nonpassive materials as well, but other processes are also likely to be important.

Finally, the OSRA model deals with a point patch (a material particle only) and does not resolve mixing processes or, given the lack of small-scale detail, much of the stirring process. Different realizations of the random aspects of the movement come only from wind drift variability, not from the oceanic currents. Vertical redistribution of the material by turbulent mixing is not included, although this may result in dilution, reduced evaporation, different transport (because of vertical shear in the horizontal currents), and enhanced horizontal mixing (e.g., vertical shear dispersion). These points indicate that, in assessing the adequacy of a practical model for a task such as oil-spill risk analysis, one needs to evaluate the potential transport, stirring, and mixing caused by many different processes.

WHAT INFORMATION IS NEEDED

Modeling Circulation and Oil-Spill Movement

Although the panel cannot specify precisely what information will provide estimates of a given precision, it is clear that to make predictions of trajectories of water and oil, a model of the current field that is in quantitative agreement with observations is needed. Although the closeness of agreement desired is a policy decision, requiring input from sensitivity runs of an impacts model, the panel believes that present numerical models substantially fail to represent present observations of the current field on and in the vicinity of Georges Bank. Improved models and observations needed for model calibration and verification will need to characterize seasonal mean circulation better; low-frequency currents induced by winds and major current excursions tidal currents, including internal tides; and variations in mixing.

It is important to recognize that all numerical models are inherently limited in their predictive capability. Lorenz (1969) demonstrated that a model calculating from initial conditions derived from data would diverge from the actual system within a finite predictability time. Two factors were responsible: errors in measurement of physical quantities such as flow and uncertainties in the values at points where no measurements were taken. Although the predictability depends on the model dynamics, the physical processes incorporated in his model have similarities to those acting in the atmosphere and in the ocean. Using new data to readjust the model ("data assimilation") greatly improves the predictions but cannot eliminate the errors (as is obvious in weather forecasting). Errors in model dynamics and in the forcing applied will also limit predictive capabilities. Finally, similar loss in predictability occurs spatially in trying to extend information into a region where there is inadequate or no data,

The extent of our ability to predict the trajectory of an actual spill is important for spill containment and management, and is relevant to leasing decisions. But there is also another, related, question: how well can we predict the statistics of the dispersal problem? Failure of a model to predict individual trajectories does not necessarily mean that the statistics produced are wrong; for example, the radioactive decay event cannot be predicted at all, and yet models of the statistics work extremely well. How well fluid dynamical models will reproduce the statistics of trajectories in the ocean is not known. Frisch and Orszag (1990) caution ". . . it is well known that detailed properties of turbulent flows at far-off times cannot be predicted. However, even the statistical properties of these flows maybe 'incomputable.' . . . [This] would imply, in the context of meteorology for example, that while the weather clearly is not predictable at long times, neither, in fact, is the climate." (Note that "far-off" is measured at the time scales of the dominant motions as described above; it might be only days.) Again, the ability to predict statistics will depend on the nature of the dynamics of the system, the degree to which the model resolves different scales, and the reliability of the statistics of the forcings and boundary conditions. It is simply not known how well even an optimal model could do, although models have clearly had some success in some places (e.g., Jayko and Spaulding, 1989). The panel emphasizes the. need for data, both as independent estimators of trajectory statistics and as input and verification for modeling.

Chronic Discharges

Chronic discharges that might have adverse ecological impacts are more likely to occur during development and production than at earlier stages. Thus, there is a need to integrate appropriate knowledge pertaining to the inputs, fate, and effects of expected chronic discharges before development and production occur. The physical oceanographic component of the required information should consist of robust estimates of fields of exposure-including expected duration-to chemical contaminants for valuable living resources in and near a lease area.

In addition, physical oceanographic knowledge must be sufficient to estimate oil spill trajectories for projected specific sites of production and transport (e.g., platforms, pipelines, and barge and tanker routes) for a lease area. The uncertainties associated with the above estimates must be provided.

PHYSICAL OCEANOGRAPHY OF GEORGES BANK

The following sections summarize the state of knowledge of the physical oceanography of Georges Bank and the use of this knowledge for the evaluation of potential environmental impacts on the bank. The first sections consider the various important physical processes that control the movement of oil, gas, and drilling muds associated with petroleum exploration and development. The next sections consider the manner in which the available physical oceanographic information is used by MMS in the preparation of EISs. The concluding sections identify the shortcomings in the present state of knowledge (or practice) and present suggestions on programs to correct these identified deficiencies that could be carried out within a reasonable length of time and with the use of a reasonable amount of resources.

Present State of Knowledge

Georges Bank is a shallow submarine bank that nearly cuts off the Gulf of Maine from the Atlantic Ocean. Principal communication between the waters of the gulf and the Atlantic occurs through the relatively deep Northeast Channel (sill depth of 230 m), which defines the eastern end of Georges Bank, and to a lesser extent through the shallower Great South Channel (sill depth of 75 m), which separates the bank from Nantucket Shoals and Cape Cod.

Mixing and Exchange

Small Scale (1-1000 m)

Small-scale mixing on Georges Bank is generaUy considered to be at a relatively high level and to result primarily from tidally generated turbulence (e.g., Bigelow, 1927; Flagg et al., 1982; Csanady and MagneU, 1987). This conclusion is based largely on (indirect) inferences from hydrographic (e.g., vertically weU-mixed areas) and current (e.g., enhanced variance) distributions, with quantitative support from a crude energy criterion for the barotropic tidal current (Garrett et al., 1978). Other significant contributions to small-scale turbulence on the bank are expected to come from breaking surface waves, wintertime convection, and shear instabilities in flows of other origin (e.g., wind-driven currents). However, measurements of the turbulence levels and verification of the generation mechanisms have not been published.

Considerable spatial and temporal variability in the small-scale turbulence levels on Georges Bank is expected. Turbulence generated by the barotropic tidal current is inferred to be most intense in the year-round mixed area inside the 60-m isobath and in the lower part of the water column (e.g., Loder and Greenberg, 1986), with its main temporal variability on the time scales of the semidiurnal tidal period and the tidal modulation cycles. The contributions from wind-driven currents and convection are expected to have magnitudes and variations similar to those in neighboring shelf regions (e.g., Brown and Beardsley, 1978; Oakey and Elliott, 1982); that is, the wind-generated component varies with storms and is most intense in the upper part of the water column, both contributing most in winter and both having limited horizontal variability except in frontal regions. Turbulence associated with breaking waves is particularly important to the vertical mixing of any surface oil slick (e.g., NRC, 1985) and may be enhanced over the central shoals of the bank, where wave-refraction calculations indicate converging wavetrains (Earle and Madsen, 1987). Over the stratified shoulders of the bank in summer, internal waves generated at the bank edge (e.g., Butman, 1987b) may be an important turbulence source for mid-depths.

For most of the bank, this small-scale turbulence is considered to be the dominant mechanism of both vertical mixing and vertical exchange over the entire water column, with associated time scales ranging from the order of hours for the bank plateau (e.g., Flagg et al., 1982; Loder et al., 1988a) to days or perhaps weeks for the seasonally stratified deeper areas.

This exchange is important to both scalars (e.g., temperature and pollutants) and dynamical properties (e.g., momentum); the vertical mixing rate of the latter, usually parametrized as a vertical eddy viscosity, has a significant influence on all components of the circulation. Over the sides of the bank and in frontal zones, it has been suggested (e.g., Hopkins and Garfield, 1981; Loder and Wright, 1985) that upwelling and downwelling associated with the seasonal-mean and low-frequency currents also contribute to Vertical mixing and exchange; theoretical models predict vertical velocities as large as 10 m/day, but such circulations have not been observationally verified. Periodic vertical displacements over distances of tens of meters are associated with internal waves and tides (e.g., Marsden, 1986), but these do not usually result in mixing or net exchange.

Small-scale turbulence is also an important mechanism for horizontal mixing but only over short distances (typically, less than a kilometer) when it acts alone. However, in conjunction with stirring processes, small-scale turbulence is an important factor in “larger-scale mixing (see below). Horizontal exchange over short distances (relative to the reference frame of the seafloor) is dominated by advection, primarily because of the tidal currents.

The moderate-to-high rates of small-scale mixing and vertical exchange on Georges Bank have important implications for the fates of drilling discharges and oil spills. On the one hand, the upper plume associated with drilling discharges should be rapidly dispersed and diluted and hence not have any significant environmental impact (NRC, 1983}, On the other hand, the downward transport of surface oil should be enhanced, possibly leading to interaction with the seafloor and its biological communities (NRC, 1985). ‘In addition, the vertical mixing rates have important implications for the fate of the main plume of drilling discharges and its interaction with the seafloor (also see the section on sediment transport below).

Intermediate (1-10 km) and Large (> 10 km) Scales

For large scales, horizontal exchange on Georges Bank occurs primarily through a combination of the seasonal-mean circulation, low-frequency current events such as those associated with Gulf Stream rings and storms, and tidal current dispersion (Flagg et al., 1982; Butman and Beardsley, 1987a; Csanady and Magnell, 1987). Information comes from hydrographic distributions, moored current measurements, drifter trajectories, and theoretical models. The seasonal-mean circulation dominates exchange in the around-bank direction and to the west, entrainment by Gulf Stream rings dominates exchange across the shelf break to the south, tidal dispersion dominates exchange over the central bank, and the contribution from storms is greatest in the near-surface region and in winter. Other processes such as bolus detachment from fronts are also expected to contribute (e.g., Csanady and Magnell, 1987), particularly in the absence of ring and storm events. The tidal dispersion mechanism is believed to be similar to that occurring in other tidally energetic shallow seas and to involve some combination of a cascade of shear dispersion processes and chaotic stirring by the tidally induced residual circulation (e.g., Zimmerman, 1986),

In conjunction with small-scale turbulence and intermediate-scale processes such as shear dispersion associated with vertical shear in the tidal currents (e.g., Garrett and Loder, 1981), these exchange mechanisms lead to large-scale mixing and reduced concentrations for materials in the water.

Two intermediate-scale phenomena that may offset, and locally dominate, the tendencies of most motions to stir and dilute materials are surface and near-bottom convergence zones associated with the seasonal-mean, low-frequency, and internal-wave flows. Of particular significance to oil spill movement and concentration on Georges Bank is the possible occurrence of surface convergence zones at the shelf break and summertime tidal fronts. Observational evidence from elsewhere (e.g., Simpson, 198 1), theoretical models (e.g., Loder and Wright, 1985), and preliminary observations from a current Canadian study on the northeastern bank (Loder et al., 1988b) suggest such an occurrence for the tidal front, but the magnitude, extent, and persistence of convergence remain uncertain. Theoretical models (e.g., Loder and Wright, 1985; Tee, 1985, 1987) for nonlinear tidal current interactions over the bank sides and over sand ridges such as those on the central bank predict both surface and bottom convergence zones, but the predicted cross-isobath residual current patterns have not been observationally verified. There may also be surface convergence zones (e.g., Shanks, 1987) associated with the large internal waves observed on the flanks of the bank (e.g., Butman, 1987b). The implications of any convergence zones for the fate of materials on Georges Bank must, however, be interpreted in relation to the energetic dispersive and advective processes that are known to occur.

Although the mechanisms that contribute to large-scale exchange and mixing have been largely identified, only "bulk" (heavily averaged in space and time) estimates of the associated rates are available (e.g., Flagg et al., 1982; Csanady and Magnell, 1987). These estimates come primarily from drifter trajectories, property budgets, and moored current measurements at a limited number of sites and are generally considered to be accurate to about a factor of two.

For the central bank in summer, the effective horizontal dispersion coefficient, appropriate to the whole water column and horizontal scales of order 50 km, has been estimated from a heat budget to be about 200 m^2/s on average, implying a residence time (for the central bank) of about 30 days (Loder et al., 1982). For the surface layer in the entire Georges Bank region, drifters suggest that the residence time is 45 and 66 days in winter and summer, respectively (Flagg et al., 1982). Moored current measurements suggest that the residence time of subsurface waters is greater. Residence time estimates for other parts of the bank are also available but have very limited statistical reliability. A wide range of values (100-5000 m^2/s) for the horizontal dispersion coefficient on the 50-km scale has been computed from near-surface drifter trajectories (Flagg et al., 1982), but the statistical reliability of the estimates and the contributing processes are unknown: the stirring (but not necessarily mixing) influence of differential advection appears to be a major contributor, but aliased contributions from the strong tidal currents may also be included. Exchange rate estimates in the form of volume transports in winter and summer are available for selected locations (e.g., shelf break, transport to the west, around-bank flow) and particular processes (Flagg et al., 1982), but there are discrepancies in some cases. For example, estimates of the average off-bank transport by Gulf Stream rings range from 0.03-0.12 sverdrup (Sv) (Butman and Beardsley, 1987b) to 0.22-0.54 Sv (Flagg et al., 1982). Thus, a detailed and consistent quantitative description of the spatial and temporal structure of horizontal mixing and exchange, and of the contributing processes, is not available.

Tides

As a result of Georges Bank's location in the near-resonant tidal system of the Bay of Fundy and Gulf of Maine (e.g., Garrett, 1972], Georges Bank has strong tidal currents that are an important factor in circulation and mixing. The tidal currents account for a large fraction of the energy in the current regime of the bank, with over 80% of the total current variance found in five principal constituents in the diurnal and semidiurnal bands (Moody et al., 1984). These currents, with typical speeds of 1 m/s, usually dominate the instantaneous current and hence horizontal advection on the time scale of hours and less, with associated water parcel excursions (tidal ellipse axes) of order 10 km. Thus, material released into the ocean is rapidly transported over this distance (relative to the seafloor), and material fixed to the seafloor is rapidly exposed to waters separated by this distance. The tidal currents also contribute significantly to the residual circulation (e.g., Loder, 1980), vertical mixing (e.g., Garrett et al.,' 1978), horizontal dispersion (e.g., Loder et al., 1982), occurrence of seasonal fronts (e.g., Flagg, 1987), and distribution and transport of sediment over the bank (e.g., Butman, 1987b). Furthermore, in areas (such as the sides of the bank) where there are significant horizontal current variations on the scale of the tidal excursion, the tidal currents contribute to Stokes velocities (e.g., Loder, 1980), which complicate the inference of water parcel movement from moored current measurements.

Tidal elevation measurements are available for about 20 locations in the bank region (Moody et al., 1984), allowing determination of the harmonic constituents and production of cotidal charts for the major ones. The elevation amplitudes are less than a meter (Brown and Moody, 1987), so that the surface elevation changes do not have a significant direct influence on the exchange of water and materials. Nevertheless, knowledge of the tidal elevation is required for the specification of boundary conditions for, and the observational verification of, numerical models of the tides. Models of the dominant semidiurnal M_2 tide (e.g., Greenberg, 1979) are in good agreement with the observed elevations and provide predictions of the tidal elevation over the entire bank.

Measurements of the tidal current constituents are available for about 30 sites in the bank region, typically for several depths at each site (Moody et al., 1984). The tidal currents at other locations are less accurately known than the elevations because of the currents' increased spatial structure associated with topographic variations. The observations indicate that the tidal currents are dominated by their barotropic component in most places (Brown and Moody, 1987), with the strongest currents generally occurring in the shallowest areas. Comparisons between the observed currents and the M_2 tidal currents predicted by Greenberg's (1983) numerical model (e.g., Marsden, 1986) indicate that the model can predict the barotropic current's spatial structure away from subgrid-scale (<7 km) topographic features, although a comprehensive comparison of observations and model predictions does not appear to have been done. Differences between the observed and predicted depth-averaged M_2 currents are typically about 5% for amplitude and 10° for phase. At most sites, the observed tidal currents have vertical structure with reduced amplitudes near the seafloor and phase changes of about 20° (e.g., Moody et al., 1984). This structure is in reasonable agreement with that predicted by models for frictional influences on the barotropic tide (e.g., Brown, 1984; Loder and Wright, 1985).

Less is known about the magnitude and occurrence of baroclinic tides on Georges Bank, although theory and observations from similar oceanographic regimes (e.g., Lee and Beardsley, 1974; Petrie, 1975; Sandstrom and Elliott, 1984; Holloway, 1987) suggest that the barotropic tidal flow over the steeply sloped sides of the bank should result in a variety of internal wave forms, particularly during the spring-fall stratification season, For the northern edge of the bank in summer and fail, there is accumulating evidence for both a baroclinic M_2 tide (Magnell et al., 1980; Marsden, 1986; Loder and Home, in press) and high-frequency internal waves (Sawyer, 1983), with vertical displacements of tens of meters and baroclinic tidal currents comparable to the barotropic currents north of the bank (up to 20 cm/s). The baroclinic tide contributes to large- cross-isobath eddy heat fluxes in the semidiurnal band (Marsden, 1986), which have been suggested to indicate the occurrence of cross-isobath Stokes velocities of several centimeters per second (Loder and Home, in press). Furthermore, recent observations (Loder et al., 1988b) from a Canadian field study on the northern side of the bank indicate the occurrence of an internal hydraulic jump during off-bank tidal flow at the bank edge, and its subsequent evolution into an internal bore and interns!-wave packet propagating onto the bank. Velocity microstructure measurements taken during the Canadian study (N.S. Oakey, personal communication) indicate enhanced vertical mixing in the mid-water column associated with the hydraulic jump. Observations from elsewhere and visual observations of surface bands during the Canadian study (J.W. Loder, personal communication) indicate that bands of surface convergence associated with the propagating internal-wave packet may exist, similar to those suggested by Shanks (1987) to be important to oil slick movement. Elsewhere on the bank, the possible significance of internal waves and tides is less clear. For the southern flank, Brown et al. (1982) concluded that the baroclinic tide is weak, although Butman (1987b) reported observations of strong currents associated with internal waves, and Brown and Moody (1987) noted evidence for baroclinic tides on the continental slope to the south. Strong internal tides have been observed at the head of canyons impinging on the shelf edge bordering the bank (Butman, 1988). In short, although existing observations suggest that the baroclinic tidal currents on Georges Bank are in general substantially weaker than the barotropic currents, recent studies indicate that the baroclinic tide may be an important factor in vertical mixing and cross-bank exchange in local areas such as the northern edge and possibly the southern flank.

Hydrography

Setting

Georges Bank forms a barrier that partially isolates and insulates the fresh and cold waters of the Gulf of Maine from the much warmer and saltier waters of the Atlantic continental margin.

A prominent factor is the influence of warm-core rings from the Gulf Stream. It has been apparent for some time that rings can disrupt the offshore limb of the circulation around the bank (e.g., Hansen, 1970; Halliwell and Mooers, 1979; Ramp et al., 1983). It has more recently been appreciated that rings can also significantly affect the inflow and outflow conditions in the Northeast Channel (Ramp et al., 1985; Brooks, 1987) and that rings sometimes inject dense, ringmodified slope water into the gulf, where it pools in Georges Basin and influences the upper-level flow along the northern and eastern edges of Georges Bank (e.g., Brooks, 1987).

Over the shallow part of Georges Bank, stirring by the strong tidal currents keeps the water vertically mixed, bringing cold water to the surface. The cold water is separated from warmer waters off the bank by a tidal front, inside of which the tidal stirring is sufficient to overcome seasonal and permanent stratification. As a consequence, surface waters over the crest of the bank, generally inside the 50- to 60-m depth contour, are always colder than surface waters on the Atlantic side of the tidal front and (in summer) also colder than surface waters on the gulf side of the tidal front. In satellite infrared imagery, the region of tidally mixed cold water stands out clearly, identifying the shallow crest of the bank.

On the Atlantic side of the bank seaward of the tidal front, a permanent frontal zone known as the shelf water/slope water front separates relatively cool and fresh water of coastal or shelf origin from warmer and saltier waters of the continental slope (Beardsley and Flagg, 1976). The shelf/slope front, as it is called, is a permanent but highly variable hydrographic feature that extends along the slope from Nova Scotia to Cape Hatteras. On the offshore side of the shelf/slope front, the water typically has salinities of 35-36 ppt, increasing seaward toward the Gulf Stream (Flagg, 1987). In the mean, the shelf/slope front intersects the bottom near the 100-m isobath and extends upward and offshore, intersecting the surface near the 200-m isobath. The location of the front, and especially its surface manifestation, undergo much variability. The surface front meanders laterally with amplitudes of about SO km on time scales of days to weeks (Halliwell and Mooers, 1979). Warm-core rings from the Gulf Stream sometimes rupture the surface front, with the ring's clockwise circulation bringing warm and salty offshore water shoreward onto the bank and exporting Georges Bank water seaward (Ramp et al., 1983). In such cases, the shelf/slope front may be displaced offshore 100 km or more on the eastern side of the ring (e.g., Butman and Beardsley, 1987b). When rings approach the mouth of the Northeast Channel, ring-modified slope water sometimes enters the channel, disrupting or even overwhelming the usual Maine Intermediate Water outflow around the eastern end of Georges Bank (Ramp et al., 1985; Brooks, 1987).

Other potentially important factors that may cause hydrographic variability around the bank are seasonal winds and intense storms, shear instabilities in frontal zones, propagation of trapped vorticity waves around the steep sides of the bank, interannual variations in freshwater sources from rivers in the Gulf of Maine, the Scotian shelf, and the Gulf of St. Lawrence, and large-scale variations in the penetration of ocean circulation patterns onto the shelf.

Winter

The enclosed waters of the Gulf of Maine are subjected to intense winter cooling by loss of heat to the atmosphere in the lee of the North American continental land mass. Cold air temperatures and vigorous wind mixing destabilize the surface layers, causing deep convection in the basins of the gulf (Brown and Beardsley, 1978). As a result, by late winter (i.e., March) a cold, nearly uniform layer of water extends to below mid-depth in much of the gulf, overlying. a warmer and saltier bottom water influenced by slope water inflow from the Northeast Channel. The onset of stratification in the spring produces a shallow and relatively warm surface layer, which seals off a low-salinity mid-depth layer with a prominent temperature minimum that survives the summer season. The mid-depth water, known as Maine Intermediate Water, or MIW (Hopkins and Garfield, 1979), is a prominent characteristic water type of the Gulf of Maine. MIW and surface waters from Wilkinson Basin provide "the primary advective source" affecting the temperature and salinity of Georges Bank waters (Hopkins and Garfield, 1981), and MIW is usually a prominently exported component of the outflow along the bank side of the Northeast Channel (Hopkins and Garfield, 1979). M IW also contributes to the near-bottom water known as the "cooI band" that moves southwestward along the offshore side of the bank (Houghton et al., 1982).

In the winter, near-surface stratification inside the gulf and inshore of the shelf/slope front weakens or disappears because of convective overturning, so that the thermal tidal front disappears from the top of the bank (see Fig. 2). A weak salinity (and density) front survives on the gulf side, however, separating slight [y fresh er surface waters in the gulf from those on top of the bank (Flagg, 1987). On the offshore side, the nearly homogeneous bank waters extend offshore to the shelf/slope front, where the temperature, salinity, and density increase rapidly in permanently stratified slope waters. During winter, waters over the bank and inshore of the shelf/slope front generally have temperatures of 2-6° C anti salinities near 33 ppt, whereas offshore in the upper slope water temperatures are typically IO-15" C and salinities near 35 ppt.

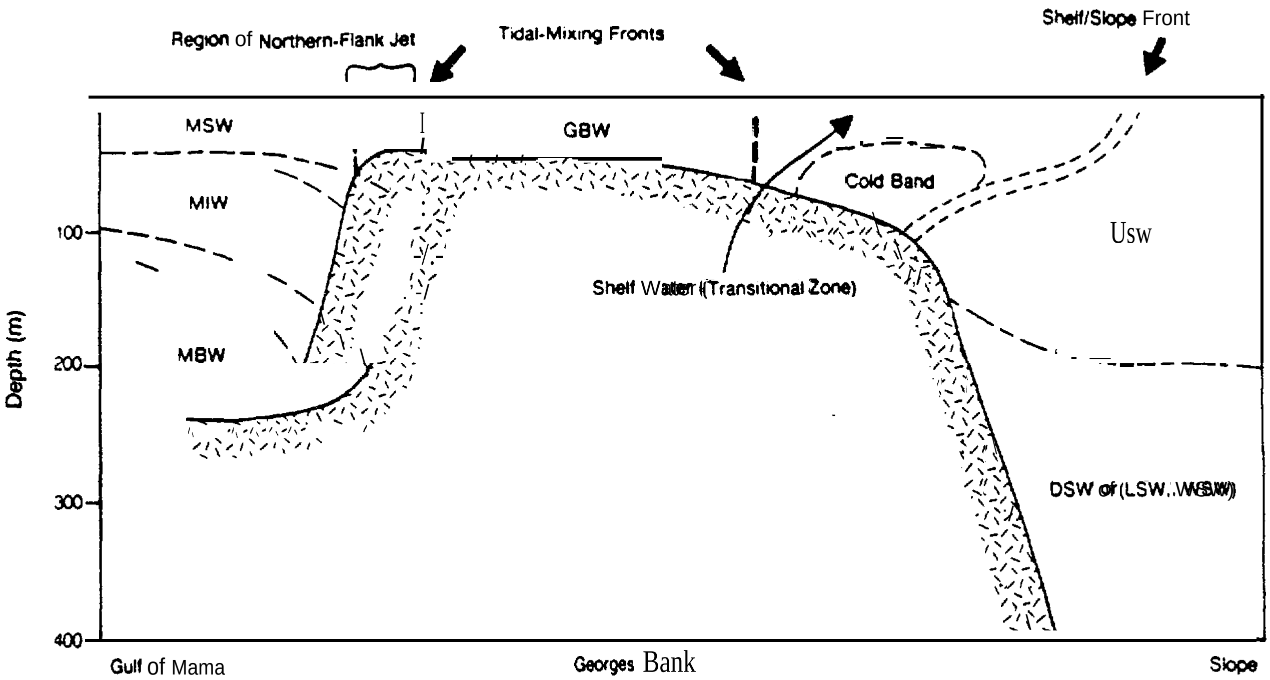

FIGURE 2 Major hydrographic features and water masses of Georges Bank in summer. (MSW, Maine surface water; MIW, Maine intermediate water; MBW, Maine bottom water; GBW, Georges Bank water; USW, upper slope water; DSW, deep slope water; LSW, Labrador slope water; WSW, warm or western slope water.) In winter the MSW and MIW coalesce, and the cold band disappears. Not shown are Scotian shelf water and Gulf Stream water. Source: Flagg, 1987. © 1987 by the Massachusetts Institute of Technology. Used by permission.

Spring and Summer

The onset of surface warming in April and May, coupled with a substantial surface buoyancy injection from the spring freshet of coastal rivers, establishes a thin, warm surface layer inside the gulf and inside the shelf/slope front (Flagg, 1987). The surface stratification on the offshore side of the bank in water deeper than about 60 m eventually becomes strong enough to resist tidal mixing, so that the tidal front reforms and gradually moves inward as the stratification increases. Further warming strengthens the tidal front and produces a shallow, warm mixed-layer "cap" over the residual winter water of the cool band, mentioned earlier (Flagg, 1987). On the gulf side, summer warming graduaUy deepens the surface thermocline to about 50-60 m by September, resulting in a three-layer "sandwich" of water masses inside the gulf: the warm surface water known as Maine Surface Water, the cold and relatively fresh MIW, and the warm and relatively salty Maine Bottom Water (MBW), which is most directly influenced by Atlantic slope water that enters the gulf as a deep flow through the Northeast Channel. Thus, in the late summer months, the surface contrasts between the well-mixed waters over the bank and the waters of the gulf and the shelf are greatest.

In the summer months, the temperature field's contribution to the density field is reinforced by the salinity field's contribution, so that strong pycnoclines surround the bank. By late summer, the salinity over the top of the bank is slightly lower than inside the gulf, and much lower than in the shelf and slope water. On both sides of the bank the pycnocline divides near

-1

30- to 40-m depth, the upper part turning Up to intersect the 'surface in the tidal front and the lower part turning down to intersect the bottom around the periphery of the bank (Flagg, 1987).

Seasonal Mean. Circulation

One of the most-cited features of Georges Bank's physical oceanography is the observed tendency for water parcels to drift clockwise around the bank (e.g., Bigelow, 1927). Sometimes described as a "gyre," this feature can be discussed as part of the "seasonal mean circulation," which is the residual current pattern after removal of fluctuations with periods shorter than 2 months (Butman and Beardsley, 1987a). It must be emphasized, however, that the strength of the seasonal mean circulation on Georges Bank is typically less than 30% of the instantaneous current speed (Butman and Beardsley, 1987a), so that the actual movement of individual water parcels is often different from that implied by the seasonal mean circulation. Thus, the implications of the seasonal mean circulation for the transport of materials in the ocean must be discussed with consideration of the tidal, wind-induced, and other fluctuating currents and vertical exchange rates.

The primary information on the seasonal mean circulation on Georges Bank comes from nonsynoptic moored (Eulerian) current measurements of variable duration (typically several months) at about 20 sites (Butman et al., 1982; Flagg et al., 1982; Butman et al., 1987). Away from the continental slope on the, southern side of the bank, the monthly mean velocities computed from these observations are generally directed nearly along isobaths, consistent with the cited clockwise gyre. Other features of the seasonal mean circulation pattern include a decrease in current strength with distance below the sea surface, increased current strength in a narrow (order 20 km) band on the northern flank, and a seasonal variation (approximate doubling) in current strength with peak values in late summer. A quantitative description of these features with uncertainties of less than 50% is available for a few locations (e.g., Butman et al., 1987). Quantitative information on the relative strengths of this circulation and of the tidal and other fluctuating currents is also available from the moored time series (e.g., Flagg et al., 1982; Butman et al., 1987), indicating that the seasonal mean circulation is generally much weaker than the tidal currents but of comparable magnitude to the "low-frequency" (periods of 2 to 60 days) currents. The "along-isobath" (i.e., parallel to local isobaths) circulation is described least well for the continental slope region, owing to the strong low-frequency variability there associated with Gulf Stream rings (Butman et al., 1987). Observations from elsewhere along the shelf break (Flagg, 1977), however, suggest southwestward mean transport. The detailed spatial structure of the seasonal mean circulation is also poorly known in the Great South Channel region, where there appears to be a large seasonal change in the amount of recirculation (Butman et al., 1987).

Secondary information sources for the seasonal mean circulation (e.g., near-surface Lagrangian drifter trajectories, dynamic height computations, and water mass distributions) are qualitatively consistent with the along-isobath component of the Eulerian pattern (e.g., Butman et al., 1987), suggesting that the moored measurements resolve the broad spatial structure of the clockwise, drift. Some Lagrangian drifters complete a circuit of the bank in summer, confirming that the seasonal mean circulation pattern is important to long-term transport, but most drifters leave the bank without completing a circuit, suggesting that other current components are important as well. The collective evidence suggests that the average time required for a complete circuit in the near-surface seasonal mean circulation is about 50 days, somewhat less in summer and more in winter (Flagg et al., 1982). The Eulerian measurements suggest that the recirculation time is up to a factor of 2 greater below the surface layer (Flagg et al., 1982). The Lagrangian observations are not adequate to determine whether there is a significant quantitative difference between the Lagrangian and Eulerian seasonal mean circulation patterns, as has been predicted (Loder and Wright, 1985).

Although the strongest, the along-isobath clockwise drift is only one component of the seasonal mean circulation on Georges Bank; "cross-isobath" (i.e., horizontal and normal to isobaths) and vertical components may also exist. The moored measurements indicate that the cross-isobath mean currents are typically only a few centimeters a second (e.g., Butman et al., 1987) and hence are generally much weaker than their alongisobath counterparts and more than an order of magnitude smaller than the instantaneous cross-isobath currents, Nevertheless, if such currents have a consistent direction around a significant fraction of the bank, they are large enough to be important to cross-bank exchange (Loder and Platt, 1985). A consistent spatial and temporal pattern in this current component has not been identified, however. Probable complicating factors are the predicted cross-isobath structure in the currents on the scale of about 10 km (e.g., Tee, 1985), the predicted cross-isobath Stokes velocities of comparable magnitude to the mean Eulerian currents (e.g., Loder and Wright, 1985), and the difficulty in obtaining accurate measurements of a weak mean current in the presence of strong tidal currents. Lagrangian drifter and hydrographic observations indicate that significant "cross-bank" mean transport does occur in two areas: on-bank flow at the bank's western end, where the along-isobath drift is partly supplied from the western Gulf of Maine, and off-bank flow at the southwestern corner, where the westward drift continues into the Mid-Atlantic Bight (e.g., Butman et al., 1987). Only rough estimates of the associated transports are available, however, suggesting that up to about 60% and 20% of the along-bank transport on the southern flank recirculates through the Great South Channel in summer and winter, respectively (Butman et al., 1982).

No direct measurements of the vertical component of the seasonal mean circulation are available. On the basis of hydrographic distributions, it has been suggested (e.g., Hopkins and Garfield, 1981) that upwelling is associated with cross-bank flow over the sides of the bank, but, with the uncertainties associated with measuring the cross-isobath flow, this suggestion has not been substantiated.

The observational description of the along-isobath component of the seasonal mean circulation is supported by idealized dynamical models that can account for most of the circulation's major features (Butman et al., 1987). The principal forcing mechanisms are the rectification of tidal currents over the sloping sides of the bank (e.g., Loder, 1980; Greenberg, 1983), and horizontal density gradients (e.g., Flagg et al., 1982; Loder and Wright, 1985) associated with differential tidal mixing over the bank and with the salinity contrast between the shelf and slope water masses (both at the shelf break and in the Gulf of Maine). The least-understood feature of the along-isobath circulation is the strength of the southwestward flow on the southern flank. The dynamics of the cross-isobath circulation are poorly known (Butman et al., 1987). Idealized dynamical models suggest that there should be a significant cross-isobath mean flow associated with the mechanisms contributing to the along-isobath circulation (e.g., Loder and Wright, 1985), but the predicted currents are not consistent with those observed (Butman et al., 1987). In the case of tidal rectification, recent theoretical advances (e.g., Ou and Maas, 1985; Maas and Zimmerman, 1989) suggest that the lack of agreement between models and the cross-isobath current observations is at least partly due to the neglect of baroclinic tidal currents in the rectification models. The existing idealized models for tidal rectification and density-driven circulation (e.g., Loder and Wright, 1985; Tee, 1985) also predict vertical velocities of order 0.0001 m/s (10 m/day), but, again, such velocities (and the models) have not been observationally verified.

Quantitative information on the interannual variability of the seasonal mean circulation on Georges Bank comes largely from moored measurements obtained over a 4-year period at one site on the southern flank of the bank (Butman and Beardsley, 1987b). The observations indicate that the seasonal variation in the along-isobath current, and also in the cross-isobath current at two of four measurement levels, exceeds the interannual variation. Moored measurements from a nearby shelf region (Smith, 1983, 1989) also indicate that the interannual variation is less than the seasonal variation. Furthermore, the known role of the tidal currents in driving the seasonal mean circulation is consistent with its interannual persistence. On the other hand, some interannual variability can be expected for the density-driven component of the circulation, associated with variability in freshwater runoff, surface heating, slope water intrusions into the Gulf of Maine, and Gulf Stream position; however, this variability has not been quantified.

Low-Frequency Variability

Prediction of the variability in the currents and hydrographic structure on the bank is an essential part of the oil spill prediction problem. These time-dependent flows are frequently comparable to (and sometimes dominant over) the mean currents and, unlike the tidal currents, have long time scales so that they can transport material fairly large distances. A substantial part of the horizontal stirring and exchange of Georges Bank waters is accomplished by these mesoscale flows. In simple mixing theory, the diffusion rate is proportional to the mean square velocity times the time scale; a similar expression describes how the probability of finding a parcel of tracer evolves. Thus, although the tides are large amplitude and cause strong local mixing, their time scales are short and the range of motion of fluid is relatively small (though important for predictions on times scales of hours to days); conversely, the seasonal and mean circulations in many locations have smaller flow speeds so that the excursion over the time scales of interest for oil and 'gas spills is smaller than those induced by low-frequency motions. Mean and low-frequency currents are relatively weak over the central bank.

Several mechanisms are responsible for the. motions with characteristic time scales of 2-20 days, the motions that dominate the low-frequency variability in water depths less than 200 m. The winds vary as weather systems pass over the region, and strong events-particularly winter storms—can create strong accelerations and transport material up to 100 km in a few days. The forces associated with tidal rectification vary with the spring/neap tide cycle, leading to longer-term variability. (The nonlinear terms, of course, make the response of the fluid to a given forcing frequency have a much fuller spectrum.) Instabilities in the seasonal mean circulations (e.g., meandering of the jets around the bank) give rise to fluctuating currents. Shelf waves can propagate rapidly along the bank. The characteristic phase speeds are 400-800 km/day, oriented so that the shallow water is to the right. Finally, forcing from the Gulf of Maine and the deep ocean is an important source of variability in the flow on Georges Bank. The changes in wind patterns over the Gulf of Maine lead to flows in and out through the channels, both directly driven at the surface and indirectly forced at depth, that may partially cancel the surface inflow/outflow. These currents lead to pressure gradients across the bank associated with the wind-driven setup in the gulf. Essentially, the bank and the Gulf of Maine react as a coupled system and must be studied as such. Furthermore, baroclinic structure is not -

included in existing models (e.g., Beardsley and Haidvogel, 1981; Wright et al., 1986) for the Gulf of Maine's response to wind forcing. On the southern side, mesoscale eddies and Gulf Stream rings (distinguished from other mesoscale variability by their formation as a cut-off loop of the stream) force fluid onto the shelf and draw filaments of shelf water out into the deep ocean. These motions have typical time scales of months and space scales of 50-150 km, leading to fairly long-term alterations in the current regime at the edge of the bank. In some cases, the eddy-induced flows are strong enough to cancel or reverse the seasonal mean transports along the bank.

The current patterns associated with the low-frequency motions have been analyzed by Noble et al. (1983) and Brink et al. (1987). In most cases, the major axis of the variance of the currents is parallel to the isobaths, although there are significant depth variations in the direction and strength of the currents, with the maximum amplitude near the surface. The anisotropy varies with location and depth; from about 2.5 to 1 on the southern flank to nearly 1 to 1 at other locations. The fluctuations are weaker at the center of the gyre. The horizontal correlation is weak, although some along-bank correlation of more than 100 km has been observed on the south side. On the north side, the along-bank correlation decays after 10-50 km. The cross-bank correlation scale is less than 15 km, generally, and the correlation in the vertical is small except for the along-isobath components in the southern region. The spatial variability in the structure of the low-frequency currents poses a difficult modeling problem, but one that needs to be addressed because these motions are important in determining the tracer distribution.

Wind fluctuations cause much of the low-frequency variability in currents on Georges Bank. Seasonally, the mean wind stress ranges from 0.1 dyne/cm^2 to the north in summer to 0.3 dyne/cm^2 to the southeast in winter. The passage of weather systems leads to much higher forcing on time scales of 4-6 days, with winter wind stresses on the order of 15 dynes/cm^2 smoothed over several days (estimated from Halliwell and Mooers (1982), taking into account their correction factors). These high wind stress periods also have definite spatial and temporal correlations (with a space scale of 500-1000 km), associated with the propagation of the storm, often from southwest to northeast. Hurricanes, though infrequent, can lead to severe wave conditions and strong currents; these extreme events may not only increase the possibility of release of pollutants but also decrease the ability to predict and contain the spread of material.

The wind-driven flows cover a wide range of time scales from 2 to 30 days. These currents are faster in winter, reaching 10 cm/s. The response of the water is dominated by the along-shelf wind component. Setup by the wind in the Gulf of Maine causes transient currents on the bank and can be expected to generate along-bank pressure gradients. However, the transient currents lag the wind by about 10 hours, with a veering of the currents to the right of the wind direction. Despite the large scales of the wind patterns, the spatial correlation of the water movements decreases rapidly. Perhaps the flow is broken up by topography or altered by interaction with the mean flows and/or front and so becomes uncorrelated. Note that the response is not local; the wind-generated motions are much more complex than a simple wind drift at an angle to the local wind. Rather, the pressure gradients can cause responses on the bank to wind changes in the Gulf of Maine and, through generation of various low-frequency waves, motions whose timing is unrelated to local wind events,

The more transient and stronger wind events (e.g., winter storms) perturb the sea surface significantly and indirectly. The pressure and horizontal flow build up quickly in response to the setup. When the storm passes, one might expect this disturbance to move around the bank as an isolated shelf wave. (Other waves are generated by the initial transients as the storm enters the Georges Bank region.) Up to 50% of the low-frequency variance can be accounted for by wind driving, including storms.

Gulf Stream rings, traveling in the slope water, affect coastal areas by pushing water onto the shelf in some regions and drawing it off in other areas (Butman and Beardsley, 1987a; Flagg, 1987) (see Fig. 3). Satellite imagery often shows the result of these flows; in the case of Eddy Q, the shelf/slope front moved 50 km onshore ahead of the ring and came off the shelf in filaments 20 km wide extending at a rate of 25-45 km/day around the eddy. These features appear to extend 50-105 m deep; the offshore transport was 0.6 Sv, compared with the along-shelf transport of 0.2-0.5 Sv. In the Northeast Channel, ring-induced flows can reverse the usual outflow of Maine Intermediate Water and redirect some of the surface flow across the channel toward Browns Bank, The enhanced geostrophic shear that results may sometimes be strong enough to redirect part of the water in the Georges Bank jet toward Nova Scotia or across the channel toward Browns Bank (Brooks, 1987). Thus, rings can indirectly cause variability inside the gulf and even along the inner edge of Georges Bank, as well as in the inner part of the channel. There is considerable interannual variability in the rate of production of rings (Brown et al., 1986).

Mesoscale eddies are similar to Gulf Stream rings in their nearly geostrophic dynamics and their Rossby wave propagation processes, but they are weaker and cover a broader range of space and time scales. There are many generation mechanisms for mesoscale variability. Wind changes over longer periods can force motions with mesoscale dynamical balances, but these changes are probably not the major cause. Instabilities of larger-scale flows are thought to be a major source for eddy motion; small variations in a smooth flow can grow by extracting either kinetic or potential energy from the mean flow. The flow rapidly loses its smooth, steady character, becoming spatiaUy and temporally highly variable and also unpredictable (at least for any single event—it may still be possible to predict the frequency and average intensity of events). This process is also not local, in that energy generated in one area may propagate as a wave to other regions. Thus, radiation of Rossby waves from the strong currents of the Gulf Stream could lead to significant motions at the shelf edge. The fluctuating currents involved in the mesoscale eddy field have an impact on the circulation and exchange at the edge of the bank that is similar to but weaker than that of Gulf Stream rings.

Sediment Transport

Sediment transport processes on and around Georges Bank are characterized by large spatial and temporal variability. Spatial variability in the surface sediments and sedimentary structures has been revealed by extensive mapping (e.g., Twichell et al., 1987). Spatial variability is affected by both the sources of bottom sediments and exposure to varying degrees of physical forcing. Major regions of surface sediments and implied patterns of transport may be described as follows (from Backus, 1987b, and Twichell et 'al., 1987):

1. The top of the bank (<60-m depth) is generally made 'up of medium to coarse sand and gravel, deposited at the end of the last ice age by retreating glaciers and by glacial outwash. These sediments have been reworked by the strong tidal currents and surface waves on top of the bank into a number of scales of bedforms. The largest are northwest-southeast trending ridges that may be 7S km long and are about 10 km apart (Uchupi and Austin, 1987). Superimposed on these are northeast-southwest trending sand waves, as long as 7 km and up to 20 m high. These are in turn covered by smaller ripples and megaripples. The orientations of the smaUer bedforms suggest a general off-bank transport, There is very little fine silt and clay on top of Georges Bank; most of it has been winnowed out by the strong currents and transported off-bank, and there is no major present-day source of silt or clay.

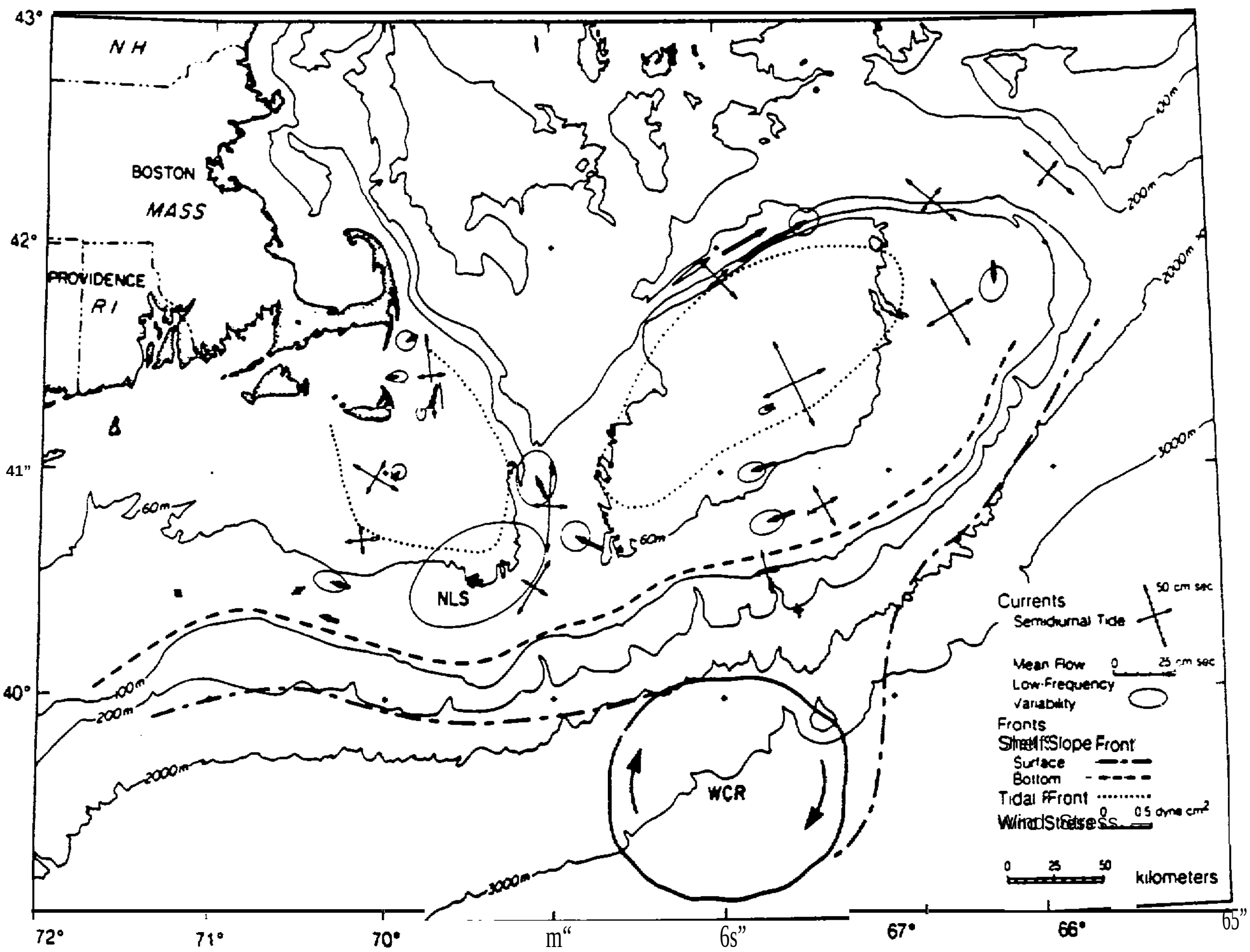

FIGURE 3 Major aspects of the physical oceanography of Georges Bank. (NLS, Nantucket Light Ship.) The approximate location of the tidally induced front (summer only) and the positions of the surface and bottom of the shelf-water/slope-water front are indicated. A Gulf Stream warm-core ring (WCR), located along the southern flank of the bank, has broken the shelf-water/slope-water front and is entraining water from the shelf in the winter map. The rotary semidiurnal tidal currents, which do not change with season, are shown by the crossed arrows defining the major and minor axes of the current ellipse. Typical summer mid-depth monthly mean currents are shown by bold arrows. Wintertime mid-depth mean currents on the northern and southern flanks are about half as strong, and the northward flow through the G rest South Channel is weak. Subtidal currents are shown as ellipses centered around the tips of selected monthly mean-current vectors; the daily-averaged current typically can flow toward any location inside the ellipse. The strength of the subtidal currents increases in tinter, especially in the Great South Channel and on the shelf south of Cape Cod. Source: Butman and Beardsley, 1987a. © 1987 by the Massachusetts Institute of Technology. Used by permission.

2. Off the central bank, in depths between 60 and 200 m, the sediments become gradually finer. Much of this region is covered by medium to fine sand, with regions of bedload transport indicated by the presence of wave-formed and unidirectional ripples.

3. The deep basins of the Gulf of Maine and the continental slope south of the bank are regions of deposition of fine silt and clay, at least some of which has been winnowed from the top of the bank. The vicinity of the heads of the canyons that incise the southern flank of Georges Bank also show some tendency toward finer sediments, although the detailed sediment distributions and sediment transport patterns in the canyons are quite complex and show evidence of active transport (Cooper et al., 1987).

4. Weaker tidal currents at relatively shallow depths (50-150 m) on the cent inental shelf south of Martha's Vineyard have created an area of active deposition of silt and clay, known as the Mud Patch, which is unique on the outer continental shelf of the Mid-Atlantic Bight. Mud Patch sediments are as much as 95% silt and clay, collected in a modern deposit that is as much as 13 m thick in places. Both mineralogical and radiochemical tracer data (Barrington, 1987) suggest that the Mud Patch is a sink for finer sediments from the more active areas of Georges Bank.

The temporal variability of boundary layer and sediment transport processes on and around Georges Bank equals or outweighs the spatial variability. The primary cause of the extreme temporal variability of the near-bottom environment is the high degree of nonlinearity associated with both physical forcing and sediment response (e.g., Smith, 1977; Grant and Madsen, 1979), such that short-lived events can dominate the long-term mean (e.g., Butman, 1987a). Sediment resuspension and transport are driven by the turbulent stresses generated by the instantaneous sum of the currents near the bottom. For single-component flows, bottom stress is roughly proportional to the square of the current speed. However, when a number of current components at widely separated frequencies are acting simultaneously, the resultant bottom stress is greater than the sum of the individual bottom stresses, and it may even be greater than indicated by the square of the sum of the individual current components. This point has been demonstrated theoretically for combined surface waves and currents (Smith, 1977; Grant and Madsen, 1979) and for combined surface waves, internal waves, and currents (Sanford and Grant, 1987), and it has been shown in the field (Grant et al., 1984) for combined surface waves and currents. The sediment response adds an additional layer of complexity. Sediments such as those found over most of Georges Bank do not move until some "critical" stress is reached; then total transport increases rapidly (to some power of > 1) with increasing bottom stress. Sediment motion in turn affects the hydrodynamics of the boundary layer, either through changes in the bottom roughness (e.g., Grant and Madsen, 1982) or through stratification of the boundary layer flow by suspended sediment (Glenn and Grant, 1987). Biological modification of the sediment-water interface and compaction of fine, cohesive sediments between transport events can lead to further changes by modifying the "critical" stress for erosion (Newell et al., 1981; Grant et al., 1982).

Butman (1987b) has identified four physical forcing processes that, acting either independently or in concert, are most probably responsible for much of the sediment transport that occurs on or near Georges Bank. These are warm-core rings shed by the Gulf Stream, internal waves, tidal currents, and storms with associated wind-driven currents and surface waves. Warm-core rings are most important on the upper continental slope, near the shelf break. Internal waves generated by the interaction of the surface tide with the bottom topography are most active during the summer near the shelf break and bank edge, over the outer continental shelf, and in the submarine canyons. Tidal currents are important because, unlike the other three processes, they are always present; sediment transport due to tides alone is probably important only on top of the bank, but the ubiquitous presence of the tidal currents may be quite important over much of the rest of the bank when combined with other near-bottom flows. Storms and associated wind-driven currents and surface waves are extremely important for sediment transport in the mid-depth band between the top of the bank and the shelf break. Butman (1987a) presents evidence for tenfold to one hundred-fold increases in suspended sediment concentration during winter storms in 1978, due mostly to intense resuspension from storm wave currents near the bottom. In combination with the wind-driven currents also associated with the storms, these intense events resulted in large along-isobath transport of bottom sediments; the direction of transport, however, was opposite in the events. Reconciliation of the massive transport that can occur during storms with the existing surface sediment distribution, which more closely mirrors the mean flow distribution around Georges Bank, is a major unsolved problem for sediment transport studies on Georges Bank (and on the continental shelf in general).

A potentially important environmental effect of drilling that is directly related to Sediment transport processes, and that has been studied on Georges Bank and found to be of limited importance, is the impact of releases of drilling muds and cuttings during exploratory drilling. The influence of drilling muds and cuttings had been found previously to be limited to the immediate vicinity of drilling activity for the coarse fraction, which makes Up about 90% of the effluent (NRC, 1983). The fine, suspended fraction is carried farther downstream by ambient currents and is rapidly dispersed; this dispersion is in agreement with both theoretical predictions and direct observations (NRC, 1983). On Georges Bank, a program Of intensive monitoring surrounding exploratory drilling in 1981 and 1982 corroborated these find ing.., Most notable were the measurements surrounding a platform in about 85 m of water. Solids settled out within 200 m of the platform, altering a small patch of bottom for a short time (Batelle/Woods Hole Oceanographic Institution, 1983). Evidence of elevated levels of barium associated With drilling muds was found within 6 km of the rig, with the highest concentrations (greater than 1.8 times predrilling levels) within 500 m, but barium levels were not distinguishable from predrilling levels beyond 6 km (Bothner et al., 1987). Barium levels decreased rapidly (with a "half-life" of 0.34 year) in the period immediately after drilling ceased, Presumably owing to physical dispersion through resuspension and transport (Bothner et al., 1983). Evidence for the resuspension and transport of barium-containing fine particulates 'as found many kilometers downstream, upstream, and offshore of the drilling activity, showing rapid and wide dispersal, but the levels were very low (Bothner et al., 1987). A similar investigation carried out near a rig in 120 m of water in the Mid-Atlantic Bight (EG&G, 1982) found greater concentrations and larger impacts, but these were still limited to the immediate vicinity of the drilling activity, and the benthic community had begun to recover within the first year after cessation of drilling. A previous NRC report (NRC 1983) stated that uncertainties still exist for low-energy depositional environments that are exposed to repeated discharges over long periods of time and for extremely sensitive environments.

Impact Assessment

Three OCS oil and gas lease sales (lease sales 42, 52, and 82) have been scheduled fOr the North Atlantic; only lease sale 42 was actually held The other two sales were stopped by legal action brought primarily by the Commonwealth of Massachusetts and the Conservation Law Foundation of New England, Inc. (CLF). Lease sale 82 and the currently proposed offering (lease sale 96) were both affected by congressional moratoria that excluded significant acreage.

Lease sale 96 on Georges Bank is the most current offering and therefore is assumed to use the most up-to-date data and impact analysis tools available. The draft environmental impact statement (DEIS) for this sale (U.S. DOI, 1988a) therefore formed the primary basis for this review.

Oil-Spill Risk Analysis

The MMS's OSRA model (Smith et al., 1982) was used to assess the oil spill risk associated with potential oil and gas development in the North Atlantic. Spills were simulated for 13 launch polygons distributed in the proposed lease areas and 84 launch segments associated with tanker transport routes and import-export tanker transportation routes in the region. The probability of oil spill impacts on 43 coastal reaches (based on equal land segments or county boundaries) and 31 targets. was studied. Targets included offshore bathymetric features (e.g., the crest of Georges Bank crest, Hydrographer and Lydonia canyons, and the Northeast Channel), key islands or bays (e.g., Nantucket, Martha's Vineyard, Cape Elizabeth, and Muscongus Bay), and locations of important biological communities (e.g., puffins and sperm whales) and fisheries areas.

The conditional probabilities of oil spills bitting land resource segments or other targets are presented in an appendix to the DEIS for each spill launch point. The locations of the launch areas, land segments and resource targets (i.e., specific biological resources) are also included in the appendix. However, no trajectory data are presented for any of the launch points.

The hydrodynamic and wind data sets used as input to the OSRA model are not given in the DEIS; nor is information on any other parameter used in oil trajectory predictions, From other sources (Francois, 1988; see U.S. DOI, 1988b) and personal communications with staff of the MMS's Branch of Environmental Modeling (T. Paluskiewicz and C. Marshall), the following description emerges.

The hydrodynamics of the study area were determined by Dynalysis (Kantha et al., 1986) using a Characteristic Tracing Model (CTM) and represent an extension of earlier work in the South Atlantic (Blumberg et al., 1981). The model covered the region from 65° W to 82° W and from 23° N to 46° N with 1/4" grid. Hydrographic data necessary as input to the model were obtained from the national archives maintained by NOAA's National Oceanographic Data Center (NODC) and the Navy Fleet Numerical Oceanographic Center (FNOC) plus local sources (including MMS-sponsored observations). Data on surface fluxes (e.g., from wind stress and heat exchange) were derived from ship observations and were available from the Marine Surface Observation data set of NOAA's National Climatic Center.

The hydrographic and surface flux data were processed to provide seasonal and annual mean representations of the density and surface forcing fields. The hydrographic and surface forcing data sets were used as input to the CTM, and predictions of the seasonal and annual mean three-dimensional flow fields were made. These climatological predictions are essentiality diagnostic calculations of the steady-state flow field. The predictions of the CTM were adjusted by removing the Ekman forced flow near the surface and were then provided as input to the OSRA model.

Winds necessary as input to the OSRA model were assumed to be spatially uniform over discrete zones and were obtained from sampling of a wind transition probability matrix. The transition probability matrices were calculated assuming the wind time series could be approximated as a first-order Markov process.

The wind data used to calculate the transition probability matrices were obtained from six stations: four offshore buoys and two lightships. The buoys were located at 34.9° N, 72.9° W (41001); 4o.1o N, 73.oo w (44002); 38.5° N, 70.6° W (44004); and 42.5° N, 68.3° W (44005). Data were obtained from the Barnegut and Nantucket lightships. The buoy data were typically 3-5 years in duration and were collected in the early 1980s. The lightship data were considerably longer in duration, having started in the late 1950s or early 1960s.

The OSRA model transported the oil spills using a linear combination of the CTM-model-predicted currents (corrected for Ekman effects) plus 3.5% of the wind speed. The wind drift angle was variable and based on Samuels et al. (1982).

Five hundred trajectories per season were simulated from each launch area or segment with randomly selected start times. The seasonal hydrodynamics was assumed to undergo a step change with the change in the season. Conditional probability results are reported for the annual average case only.

Oil and Gas Blowouts

The DEIS has no discussion or analysis of the impacts of gas blowouts. Gas blowouts, however, may well be very important given the expected finds (U.S. DOI, 1988b). The Advisory Committee on Georges Bank Hydrocarbon Development of the Canadian Department of Fisheries and Oceans (DFO, 1988) has concluded that a short-lived blowout (a few days) would have no major impact on the biology of fishery resources, although tainting could occur. It indicates, however, that longer-term blowouts could have substantially greater impacts but that these would be dependent on location and timing,

In summary, the DEIS for Georges Bank in the North Atlantic (lease sale 96) does not adequately address the risks of oil spills on the environment, because the hydrodynamic input data to the OSRA model are not representative of the area, include substantial errors, and ignore several key physical processes.

Assessment of Oil Spill Risk Analysis Calculations

The oil spill risk analysis calculations have several critical weaknesses. These are summarized below

1. The CTM calculations for the hydrodynamics have never been verified by comparison to field observations for the area. A cursory examination suggests that the model predictions do not represent the large-scale flow patterns (southwesterly shelf flow) that predominate in the study area; nor do they represent the Gulf of Maine and Georges Bank gyres (Butman and Beardsley, 1987b; Butman et al., 1987). Furthermore, the boundary of the model domain on the east side (65° W) does not extend sufficiently eastward to represent accurately the flow on the Scotian shelf and its impact on the Gulf of Maine-G eorges Bank circulation. The CTM model predicts extremely large (> 50 cm/s) north-south directed mean surface currents on a substantial section of the southern New England shelf, These currents are not observed in the field (Butman et al., 1987) or in other model calculations (Isaji et al., 1982, 1984; Isaji and Spaulding, 1984). It appears from studying the predicted flow pattern that there is a substantial error in

the model predictions, caused by the formulation, the boundary condition specification, or limited local observations of the hydrographic field.

2. One of the principal circulation-forcing mechanisms in the Gulf of Maine-Georges Bank area is the tides (Brown and Moody, 1987). The tides generate strong periodic currents throughout the region, but more importantly for spill trajectory modeling, contribute to a strong clockwise residual flow around Georges Bank (Loder, 1980). This gyre-like circulation is particularly strong on the northern and eastern flanks of the bank, with a weaker flow on the southern side of the bank and through the Southeast Channel (Greenberg 1983; Isaji and Spaulding, 1984). This tidally induced gyre has a significant impact on the residual circulation and therefore on oil spill trajectories. The CTM does not include tidal forcing. MMS has not incorporated tidal circulation or tidal 'Stokes drift in OSRA model predictions.

3. In the OSRA model, the transition probability matrices used to defiie the wind are only marginally adequate to provide an accurate estimate of the mean statistics. Furthermore, the model does not account adequately for the spatial and temporal variations in the meteorological forcing fields. This problem is particularly important given the importance of wind forcing in determining spill trajectories.

4. The representation of the hydrodynamics in the CTM ignores several key features of the flow that potentially have important impacts on predicted spill trajectories. The features of principal concern are the Gulf Stream-generated rings that impinge on the shelf, the semipermanent fronts located on the flanks of Georges Bank, and the intense vertical mixing that occurs over the bank.

5. Calculations of oil spill trajectories at the sea surface and those for underlying currents are inconsistent. Specifically, the wind-induced flows used as inputs to the OSRA model to determine the wind- and wave-induced drift are 'not consistent with the wind forcing used as input to the CTM calculations.

6. 'In the CTM the effect of enhanced vertical mixing over Georges Bank needs to be incorporated into a treatment of dispersion and entrainment of oil and gas in the water column.

CONCLUS1ONS

This section summarizes (1) deficiencies in our knowledge of the relevant transport and exchange processes that control the movement and subsequent concentration of pollutants that might be introduced into the marine environment "and (2) re'uirements that must be met in order to use available knowledge in making adequate predictions of potential impacts arising from specified drilling activities. A strategy is presented for determining the priorities among selected aspects of the need to increase the physical oceanographic knowledge base and the need for improved use of available physical oceanographic knowledge in making predictions of environmental impacts that could result from drilling activities.

Strengths and Weaknesses of the Existing Data Base for Decisions

The relative importance of stirring and mixing on various scales, and hence the expected concentrations and streakiness of materials in the water, are poorly known. More information on the magnitude and scale-dependence of kinematical flow properties such as horizontal dispersion and divergence may be required. More information may also be required to quantify the amplified vertical mixing rates on Georges Bank. The rates are least well-known for the stratified areas that flank the bank in summer. The vertical mixing rates at the sea surface, for both neutral and buoyant material, are of greatest relevance to the oil impact problem. The rates near the seafloor are most relevant to the fate of the main plume of drilling discharges and to sediment transport.

Barotropic tidal currents dominate the instantaneous currents on Georges Bank. A thorough intercomparison of model-predicted tidal currents (including all major constituents and vertical structure) with those observed is needed to provide a verified basis for determination of tidally driven residual circulation and mixing.

Further information may be required on the magnitude, spatial extent, and temporal occurrence of baroclinic tides and their decay products (e.g., bores, wave packets, and turbulence), particularly along the northern edge of the bank. These features may be of critical significance to cross-bank and vertical exchange and to the concentration of surface-layer material in the summertime stratified areas along the perimeter of the bank.

Adequate information and understanding are available to obtain a lowest-order quantitative description of the along-isobath component of the seasonal mean circulation on Georges Bank. However, many details remain unknown, and the cross-isobath component of the seasonal mean circulation is poorly known, except for the fact that it is generally weak in comparison with the along-isobath component. The main areas that may require further knowledge are the cross-isobath currents in general, the extent of recirculation in the Great South Channel region, the coupling of bank circulation to the larger-scale circulation of the Gulf of Maine and the shelf/slope front, the circulation (including the vertical velocity) associated with persistent local features such as tidal fronts and abrupt topography, and the relation of water parcel movement to Eulerian current patterns.

Further information may also be required on the locations, magnitude, and variability of cross-bank exchange by all motions. In particular, there is limited information on the exchange associated with storms, Gulf Stream rings, and the seasonal mean circulation. The relative magnitudes, as well as the spatial and temporal variability, of the competing influences of dispersion and possible surface convergence zones, particularly at fronts, may need to be determined. The low-frequency variability in the Georges Bank region differs from that in most other continental shelf regions owing to the impact of warm-core rings from the Gulf Stream and to the complicating influences of topography and the adjacent Gulf of Maine on the response of the currents to wind events. Correspondingly, in this region, less is known about the low-frequency motions and their relation to the external forcing than might otherwise be expected. Further information may be required on the role of rings, wind, and other factors (e.g., inflow from the Scotian shelf) in controlling the timing and intensity of the annual cycle of slope water intrusion to the gulf, as well as its subsequent influences on region-wide circulation.

To predict major disturbances in the bank gyre with confidence, one must first understand the basic mechanisms that cause the variability, and these understandings are just beginning to emerge. More applicable models and perhaps more fieldwork are needed to understand adequately and, ultimately, to predict the complicated influences of rings on bank circulation. For example, model strategies must be extended to include the seasonal and event-driven evolution of the basic hydrographic structure around Georges Bank and in the major adjacent basins of the Gulf of Maine, because the wind- and density-driven circulations of the two areas are highly coupled. Such models will require sophisticated methods to resolve the (summer) baroclinic structure inside the gulf, while [resting the rugged bottom topography realistically. It will also be necessary to model variable effects of forcing at the boundaries, especially including the annual cycles of inflow and outflow in the Northeast Channel; buoyancy modifications by river runoff, surface heat fluxes, and inflow of Scotian shelf water; and the seasonal surface wind stresses.

As mentioned above (see Space and Time Scales), although numerical models may predict some currents that resemble the observations and perhaps have correct statistics, the prediction of trajectories may not be sufficiently accurate for risk assessment. Experiments tracking particles within Eulerian models have shown that quantities that should be constant along a track in fact vary significantly; thus, a model may not be able to move Lagrangian particles consistently (e.g., pers. comm., Dale Haidvogel, 1990; Csanady, 1990; Lozier and Riser, 1989). In addition, the statistics of particle trajectories may also be extremely sensitive to details of the dynamics, and these may not be adequately represented by a numerical model, For example, trajectories can be chaotic even in flows that are regular in an Eulerian framework (e.g., Aref, 1984) so that the predictability of individual events is extremely limited. Very little is known about predicting probability distributions of particle trajectories, even given a good estimate of the accuracy of the Eulerian fields. As Csanady (1990) said: ". . . the relationship of the Eulerian mean square velocities to Lagrangian ones is terra incognita." Until models have been adequately verified, trajectories based on field data provide the preferred method for predicting oil-spill movements,

Several major questions remaining about sediment resuspension and transport on Georges Bank center on determination of the actual rates of transport, and, to some extent, the direction of transport (Butman, 1987b). These questions include a reconciliation of event-related transport with mean patterns of erosion and deposition; the rates of supply and erosion of fine sands, silts, and clays to and from the Mud Patch and other apparent depositional environments; the influence of off-bank and off-shelf transport; and local concentration of suspended material, as possibly occurs near the canyon heads on the south side of the bank. It is conceivable that a complex numerical model linking near-bottom currents (including tides, internal waves, and surface waves) to patterns of erodibility inferred from the known surface sediment distribution, and incorporating the best of the existing boundary layer/sediment transport models, would yield a reasonable estimate of net patterns of erosion and deposition. The model would have to be run to include several different size classes of sediments. Such a model would be virtually untestable with the existing database, however.

Future MMS-funded sediment transport studies on and around Georges Bank might be focused more profitably on resolving remaining questions about the sources, pathways, and fates of the very fine sediments that are transported primarily in suspension. Long-term effects of drilling and petroleum production in the marine environment are most closely associated with these fine particulate (U.S. DOI, 1988a), which provide a preferential substrate for adsorption and accumulation of toxic metals and hydrocarbons. It is clear from existing data that shallow (<60 m) areas of the Georges Bank 'environment are too energetic for fine sediments to accumulate and that concentrations of silts and clays in the near-surface waters of the Georges Bank region are often low (Bothner et al., 1985; Batelle/Woods Hole Oceanographic Institution, 1983; U.S. DOI, 1988a). However, regions of fine sedimentary accumulation have been identified downstream and offshore of the more active environments, and these regions apparently seine as sinks for fine particulate from these active environments. Thus, the most important sediment transport problems for Georges Bank are (1) to determine where, when, whether, and how petroleum-related toxics will come into contact with fine sediments, (2) to determine how much concentration of toxics is likely to occur in depositional environments, and (3) to predict the transient concentrations (due to both physical and biological processes) of petroleum-related toxics in biologically sensitive areas. Existing data indicate that accumulations from exploratory drilling are likely to be minimal (U.S. DOI, 1988a). The possibilities of localized and/or seasonally modulated sedimentary accumulation of toxics from chronic discharges during development and production are still open questions, however. Sedimentary accumulation of undegraded hydrocarbons from oil spills transported from Georges Bank also may be a problem in remote nearshore depositional environments (Boesch et al., 1987).

Use of Available Knowledge

It should be noted that in published model results (e.g., Beardsley and Haidvogel, 1981; Greenberg, 1983; Wright et al., 1986), wind and tidal forcing, either individually or in concert, do not adequately reproduce the interior circulation in the Gulf of Maine (at least in spring and summer months); it is crucial that the baroclinic structure of water masses and their variability be included in models if the variability of currents in the gulf (and therefore along the northern edge of the bank) is to be reasonably predicted.

Although the existing information is adequate to provide a first description of the seasonal mean circulation, the information has not been fully utilized in modeling and other applications. A box transport model (Flagg et al., 1982) has been used to estimate transport across key sections in winter and summer, but it appears that this information has not been used in the OSRA model. Increased spatial resolution in such budgets, together with more recent estimates of transport and mixing, should yield further information on the transport and mixing rates implied by the hydrographic variability.

In addition, there are known processes, and existing estimates of the associated mixing and exchange rates, that apparently have not been included in existing impact models. In the OSRA model, for example, some known flow components, vertical mixing and subsurface transport, and horizontal mixing and stirring on small and intermediate scales are not included. As a minimum, the sensitivity of model predictions to these processes should be assessed. In discussions of the fates of drilling discharge plumes, the scale dependence of turbulent mixing rates is not always recognized; the (larger) mixing rates appropriate to large scales are sometimes used for the small-scale plume dispersion problem (e.g., NRC, 1983).

Numerical tidal models can provide first estimates of the tidally rectified component of the seasonal mean circulation, but this component has not been included in the OSRA model. Diagnostic models, in combination with the large hydrographic data base from the region, can be used to estimate the density-driven component of the seasonal mean circulation; these have been used to obtain currents for the OSRA model, but with only coarse spatial resolution and without any published intercomparison with the measured seasonal mean currents. The sensitivity of Lagrangian trajectories to the inclusion of tidal currents and low-frequency variability in circulation models (e.g., dependencies on the stage of the tide at the time of release) needs to be investigated.

Recommendations for Future Work

The panel has identified the present state of physical oceanographic knowledge of the Georges Bank area and the deficiencies in that knowledge that could lead to serious shortcomings in the validity of predictions of oil- (or gas-) spill motions and fates. The panel has also identified an underutilization of present knowledge in the modeling used for preparing the DEIS. What remains is to determine which of these elements limit the adequacy of the predictions on the environmental impacts of drilling activities. There is unfortunately no a priori way to make this determination; rather it must be done iteratively in a manner such as the one suggested below.

In view of the observational data base and existing understanding of the physical oceanography of Georges Bank, the priority for further work to determine the transport and exchange of oil and gas and their related products is the development of a circulation model that is consistent with observations and understanding, in conjunction with the field programs needed to provide the data for that purpose. Given the present level of knowledge, an appropriate modeling strategy might include: prediction of the circulation associated with known forcings (by tides, density, and wind) using separate models for each forcing; comparison of predictions with observed currents (both Eulerian and Lagrangian) and hydrographic structures (including the location of fronts), surface elevations, and turbulence levels; addition of further flow components to optimize model agreement with observations, or assimilation of observations into the models; utilization of observations and idealized or local models to determine suitable parameterizations for subgrid-scale processes; use of the model(s) as a research tool to investigate the sensitivity of currents and trajectories to various forms of wind input formulation, other forcings, and other poorly known parameters; and development of fully nonlinear models as the contributing processes are understood and appropriate parameterizations are identified. For some flow components, three-dimensional models may be appropriate and practical. The resulting circulation model could also be used to examine the sensitivity of particle trajectories to higher-frequency current fluctuations (e.g., tidal and storm-induced currents and warm-core rings and other eddies) and the relation of these trajectories to Eulerian currents. Application of the circulation data and oil trajectory model ‘algorithms must be tested against the trajectories for known spills or spill surrogates (e.g., a surface drifter configured to behave like oil).

Sensitivity studies, as suggested, will permit determination of the critical gaps in knowledge and the degree to which these gaps must be filled in order for satisfactory model predictions to be made. The final, and very necessary, test is that the model produce results that are verified by independent observations. There is evidence that MMS is making progress on at least some of these areas (e.g., Herring and Rubenstein, 1990),

3

Ecology

OVERVIEW

Factors that contribute to the high productivity of Georges Bank include topographical complexity, large high tides, and possibly the trophic linkages between benthic and pelagic communities. Because of its high productivity, Georges Bank, in addition to supporting important fisheries, is also an important habitat for many species of sea birds and marine mammals, including some that are endangered.

Because there is sufficient information to characterize the distribution and abundance of important biological resources, the panel concludes that for Georges Bank (lease sale 96) there is enough biological information-that is, inventories of biological resources at risk-to make an informed decision about leasing, although not all the information is well covered or properly analyzed in the DEIS. After leasing, more-detailed site-specific analyses would be needed during exploration. If commercial quantities of oil or gas are discovered, additional information will be necessary to assess the site-specific environmental impacts of development and production. The panel considers the currently available ecological information to be adequate to serve as the basis for additional investigations required for this purpose, provided adequate physical oceanographic information is available.

Ecological information is needed to assess the environmental effects of OCS oil and gas activities. Assessment generally consists of a reconnaissance survey of the environments likely to be affected, a description of the type of activity proposed, and an assessment of the type and likelihood of environmental impacts. Part of this assessment includes a review of the impacts of OCS oil and gas activities in other areas. This chapter is concerned with the application of these three parts-environmental survey, project description, and impact assessment-to ecosystems in which the activities may take place. Marine ecosystems are complex, and many of their components and processes are not well understood. This lack of understanding places limits on the precision with which impact assessments can be conducted.

Continental shelf habitats of North America represent diverse biological communities and important economic assets. The extremely high productivity of continental shelf habitats supports some of the world's most important commercial harvests of fish and shellfish. Because of the dense population centers in nearby coastal areas, continental shelf habitats are also subjected to the impacts of many human activities, including waste disposal, commercial transportation, commercial fishing, and mineral resource exploitation. These activities can conflict with each other and can compromise recreational and aesthetic values and resource use on the continental shelf. Multiple-use impacts on continental shelves are highly variable in space and time, and their interactions are difficult to understand.

A FRAMEWORK FOR EVALUATING IMPACTS

The ecosystems of Georges Bank are, like most ecosystems, complex and diverse. Many species are undescribed, can be recognized only by experts, or are too small to be seen with the risked eye. Neither OCSLAA nor NEPA provides clear guidance as to what aspects of ecosystems need to be understood for OCS decisions. The panel takes as its framework one that it considers to represent the current state of good scientific practice in the field. Chapter 10 of *Ecological Knowledge and Environmental Problem-Solving: Concepts and Case Studies* (NRC, 1986) provides general guidance for identifying important issues and components of ecosystems in impact assessment (see Table 1).

TABLE 1 Some common criteria for identifying important issues and valued ecosystem components in impact assessment

Legal requirements

- Air and water quality standards
- Public health
- Rare, threatened, and endangered species
- Protected areas or habitats

Aesthetic values

- Landscape appeal
- Attractive communities
- Appealing species (e.g., large ungulates, colorful birds, cacti)
- Species at higher tropospheric levels (e.g., eagles and tigers)
- Clear air and water

Economic concerns

- Species or habitats of recreational or commercial interest
- Ecosystem components

Environmental values and concerns

- Ecosystem rarity or uniqueness
- Sensitivity of species or ecosystems to stress
- Ecosystem "naturalness"
- Genetic resources
- Ecosystem services
- Recovery potential of ecosystems
- "Keystone" species

Source NRC.., 1986.

WHAT INFORMATION IS NEEDED

Ecological impacts of OCS activities may occur during exploration, development, and production (Table 2). Potential ecological impacts are distinct during each phase and require a different suite of studies for prediction of the extent and duration of impacts. Predicting at the time of leasing the activities that will occur in later phases is complicated by the great uncertainties surrounding estimates of oil and gas reserves. The history of OCS exploration suggests that predictions of oil and gas reserves by both MMS and the oil industry can differ widely from what is actually produced; it is not possible to predict whether, where, and how much oil or gas will be discovered. In fact, only a small percentage of exploratory wells ever lead to commercial production. For this reason, it would be difficult and expensive to conduct detailed, site-specific impact assessments for the development and production phases before leasing and exploration. Exploration activities, including seismic surveys and drilling for a relatively short duration, pose a lower potential for significant ecological impact than development and production activities. Thus, the panel recognizes that the quantity and types of ecological information needed for a decision on exploration are less than those needed for a decision on development and production of oil and gas resources. The analysis of ecological impacts for production and development is more site-specific than that for exploration and depends on the amount and location of the resource as well as its nature (i.e., oil or natural gas) and chemical composition. Indeed, reliable assessment of the potential impacts of development and production may be impossible before the results of exploration are in hand.

Information Needed for Leasing Decisions

For an informed leasing decision, a characterization of the environment, including its biological resources, and a basic knowledge of ecological relationships are needed. The desired information includes (1) a characterization of major habitat types, (2) a catalog of representative species (or major species groups) present in the lease area, and (3) seasonal patterns of distribution and abundance of representative species (e.g., identification of spawning or feeding grounds); for exploration, development and production more site-specific information is needed, including (4) basic ecological information on representative species (e.g., habitat, feeding behavior, and reproduction), (5) basic information on factors determining vulnerability of various species, and (6) the potential effects of various agents of impact (e.g., spilled oil, noise and disturbance, and other discharges). Information on factors 1 through 3 is essential at the leasing stage. In practice, region-specific information of the type needed to address factors 4, 5, and 6 is collected during exploration or before an exploration permit is granted. Where unique habitats or endangered and rare species exist, more extensive characterization of the sensitivity of biota to OCS activities, information on recovery rates, and identification of mitigating measures may be required before leasing, in such cases, information on all six factors could be needed for a leasing decision.

Information Needed for Development and Production Decisions

Before a decision is made to develop and produce, which will occur only if commercial quantities of petroleum are found, more detailed site-specific environmental analyses should be

TABLE 2 Major activities in the development of an offshore oil and gas field and their potential effects on marine and coastal environments.

Activity	Potential Effects
Evaluation	
Seismic surveying	Noise effects on fishes and mamals
Exploration	
Rig Fabrication	Dredging and filling of coastal habitats (mostly overseas)
Rig Emplacement	Seabed disturbance due to anchoring
Drilling	Discharge of drilling fluids and cuttings; risk of blowouts
Routing Rig operations	Deck drainage and sanitary wastes
Rig servicing	Discharges from support vessels and coastal port development
Development and production	
Platform fabrication	Land usc conflicts and increased channelization in heavily developcd areas
Platform installation	Coastal navigation' channels and seabed disturbance resulting from placement and subsequent presence of larger platform
Drilling	Larger and more heavily concentrated discharges of drilling fluids and cuttings; risk of blowouts
Completion	Increased risk of oil spills
Platform servicing	Dredges and coastal port development
Separation of oil and gas from water	Chronic discharges of petroleum and other pollutants
Fabrication of storage facilities and pipelines	Coastal use conflicts
Offshore emplacement of storage and pipelines	Seabed disturbances; effects of structures
Transfer to tankers and barges	Increased risk of oil spills; acute and chronic inputs of petroleum
Construction of onshore facilities transportation and storage	Coastal use conflicts; aerations of wetlands in pipeline corridors
Pipeline operations	Oil spills; chronic leaks
Refining	
Construction and expansion	Coastal use conflicts
Operations	Increascd pollutant loading (depends on regional demands); imports, etc.

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performed. Because the most common outcome of exploration is failure to discover commercially viable quantities of oil and gas, it is actually infrequent that development and production follow leasing and exploration. During development and production, the characteristics and volumes of discharged materials differ, and they are discharged for a longer period of time than during exploration. The fate of discharged materials depends on the physical processes operating at the platform site, and potential effects depend on characteristics of populations and communities at risk. The precise location of the platforms and the resource-as well as its nature arid composition-must also be known. Additional studies will generally be required during exploration to investigate site-specific factors that might influence the magnitude of impacts and the speed of recovery from them. Thus, an important question at the prelease phase of assessment is whether there is enough basic information on the environment to conduct these site-specific investigations in a reasonable time.

CHARACTERIZATION OF THE ENVIRONMENT

The Setting

As described in the introduction, most of the bank has water depths less than 100 m and some areas are as shallow as 3 m. The sides of the bank are generally steep, except at the southwest corner, and there are several submarine canyons along the southern slope. Sediment substrates on Georges Bank consist primarily of sand and gravel, with freer sediments transported off the bank by tidal currents and waves. Submarine canyons and the continental slope may be potential sinks for fine sediment (DFO, 1988). Unique features of the ocean circulation of Georges Bank contribute to the high productivity of the ecosystem. Mountain and Schlitz (1987) discuss the biological implications of large-scale recirculation and exchange patterns on the bank and suggest that these processes may contribute to annual variation in larval fish mortality. The interaction of biological and physical features on Georges Bank contributes to the variability of fish populations, and although information is far from complete, there is sufficient knowledge to test hypotheses regarding the control of recruitment and post-recruitment patterns.

Benthos

The benthic habitats of Georges Bank support important harvestable resources and trophic links in its productivity. The benthos of Georges Bank has been well characterized (Wigley and Theroux, 1981; Maciolek and Grassle, 1987; Michael, 1987) including variability in spatial and temporal distributions of organisms. In addition to the shallow bank, sedimentary features, physical processes, and benthic biota from submarine canyons have also been examined (Valentine, 1987; Butman, 1988; Maciolek and Grassle, 1989). Some submarine canyons appear to be important sites of sediment accumulation (Bothner, 1989) and thus may be a repository for chronic discharges from oil and gas activities on Georges Bank. Boehm (1989) suggested that hydrocarbons derived from oil and gas activities would be rapidly redistributed with fine-grained sediments from their point of origin and transported to depositional areas such as canyon heads, deeper slope areas, and shelf basins (e.g., the Mud Patch). The consequences of contaminant transport away from Georges Bank are largely unknown.

Trophic linkages between benthic and pelagic communities might be important in contributing to the productivity of Georges Bank. Collie (1985) examined the trophic linkages between amphipod populations and demersal flatfish populations; he found that the production rates of amphipod species on Georges Bank were as high as production rates of near-shore species. In a recent study, high-density demersal layers of krill were observed in the submarine canyons off Georges Bank, and Greene et al. (1988) suggest that these populations of krill may be an important trophic link for high production of squid and demersal fishes on the bank. The sensitivity of these communities to discharges from OCS oil and gas activities is largely unknown but could be of great importance in understanding the ecological impacts of OCS activities,

Birds

Georges Bank and its associated shelf/slope waters are important for large numbers of marine birds of several species. Powers and Brown (1987) described the distribution and abundance of seabirds on Georges Bank, based on studies conducted from January 1978 to May 1982 by the Manomet Bird Observatory (Powers, 1983) and observations made by the Canadian Wildlife Service (Brown, 1986). Thirty-two species of marine birds were observed on Georges Bank. Seasonal and spatial patterns of seabird distribution and abundance appear to be related to hydrographic conditions and food availability. Powers and Backus (1987) examined the energetic of seabird populations on Georges Bank, including identification of food preferences for different species and estimates of total energy consumption by seabirds; energy removal by seabirds on Georges Bank was found to be comparable to values estimated for other productive marine ecosystems. Three features of seabird distribution discussed by Powers and Brown (1987) that may be critical to assessment of offshore development impacts are (1) the observation of 200,000 greater shearwaters (*Puffinus gravis*) on Georges Bank in November 1977, suggesting that the bank may be an important mid-latitude staging area for this species; (2) the observation of a disproportionately large number of razorbills (*Alca torda*) found dead and oiled following the *Argo Merchant* spill, suggesting that Georges Bank maybe an important wintering area for this species; and (3) the occurrence of large flocks of red phalaropes (*Phalaropus fulicarius*) along the shelf break in spring, suggesting that the bank might be an important staging area for this species as well. Two additional inshore species deserve comment. The endangered beach-dwelling piping plover (*Charadrius melodus*) is vulnerable to oiling and has been extensively studied (U.S. Fish and Wildlife Service, 1987), as has the endangered roseate tern (*Sterna dougallii*) (U.S. Fish and Wildlife Service, 1989), which appears to be less vulnerable to. oiling than the plover. Further analysis of the sensitivity of different species of seabirds to oiling and the relative importance of Georges Bank as a habitat for different species may be required during postlease activities. Overall, there is generally adequate information to permit an informed decision concerning leasing with respect to the potential impact of oil and gas development on marine bird populations.

Marine Mammals and Sea Turtles

The Cetacean and Turtle Assessment Program (CETAP) was supported by MMS and provided a comprehensive survey of the distribution and abundance of whales, other cetaceans, and sea turtles from Cape Hatteras, North Carolina, to the Canadian border and seaward to the 1000-fathom (1830-m) isobath. This program provided an improved understanding of species distribution patterns, identification of feeding and nursery grounds, and habitat characterization

(Winn et al., 1987). Georges Bank serves as a regular or occasional habitat for more than 18 species of cetaceans, with peak abundance during spring and summer of 29,000 individuals. prominent among the cetaceans are humpback (*Megaptera novaeangliae*) and right (*Eubalaena glacialis*) whales, both listed as endangered species. CETAP provided insights into basic patterns of use of waters off New England by these two species. These insights have led to additional research and the development of a significant whale-watching industry. Data from CETAP and other sources have shown that cetaceans are significant predators on the marine resources of the northeast OCS region (Kenney et al., 1985).

Only two species of sea turtles were commonly observed on Georges Bank during CETAP (Schoop, 1987), the loggerhead (*Caretta caretta*) and the leatherback (*Dermochelys coriacea*). Both species are widely distributed over the continental shelf from Newfoundland southward. Other species of sea turtles—Kemp's ridley (*Lepidochelys kempi*) and the green sea turtle (*Chelonia mydas*)—have been reported in nearshore areas of Cape Cod but not on Georges Bank. Although detailed knowledge of migratory patterns of sea turtles is lacking, abundance of leatherbacks and loggerheads on Georges Bank during the summer suggests that Georges Bank maybe an important feeding ground.

Fisheries

The high productivity of Georges Bank results in large commercial catches of many species of fish and invertebrates. Primary production on Georges Bank has been studied for several decades, and comparative data with other temperate marine ecosystems suggest that Georges Bank is among the most productive ecosystems (Cohen and Grosslein, 1987). Zooplankton production has also been studied for decades, but Davis (1988) recently reevaluated earlier data sets from Georges Bank and concluded that zooplankton production is controlled by temperature and not food availability. It has been suggested that secondary producers from submarine canyons contribute to the production of squid and demersal fish stocks (Greene et al., 1988). Temporal distribution of the resources, egg and larval distribution, identification of spawning grounds and feeding habits, and the general ecology of most resource species are known in sufficient detail to characterize the resources at risk. Studies of population dynamics, energy flow between trophic levels, and predator-prey interactions have been characterized well enough to define at least partially the limiting factors to fish and shellfish production (Sissenwine et al., 1984; Cohen and Grosslein, 1987; Sissenwine, 1987). Sissenwine (1984) summarizes the factors that control fish recruitment and population size and suggests that predation may be the major cause of pre-recruit mortality.

Modeling

The effects of an oil spill on fisheries resources maybe direct, through the loss of reproductive or recruitment success, or indirect, through the disruption in food chain dynamics. Both types of impacts are difficult to assess because of natural variability in reproductive and recruitment success and our lack of understanding of the details of trophic linkages. Models have been developed to assess the effects of an oil spill on fishery resources. The Georges Bank model assesses the effects of an oil spill on pelagic early I ife history stages (eggs and larvae). The model is composed of four submodels: a hydrodynamic model, an oil-spill fate model, an ichthyoplankton transport and fate model, and a fish population model (Spaulding et al., 1983, 1985), Predicted encounters between ichthyoplankton and spilled oil above a threshold concentration result in mortality of eggs and larvae. The fisheries population model is then used to predict the effect of oil-induced recruitment losses. In this model, only losses of recruitment stages are considered to be important, and oil effects on juvenile and adult fish are considered to be of minor importance. This model has been applied to four commercially important fish species—haddock, cod, sea herring, and yellowtail flounder. Later models were applied to the sea scallop (French, 1988).

The Scientific Committee of the Outer Continental Shelf Advisory Board for MMS recently formed a Fisheries Task Force and commissioned a review of those models that linked hydrodynamics, oil spill fate, and fishery models (TRI, 1989). The Georges Bank model was considered to be the most sophisticated of the models examined, and specific recommendations for future development were made (Fletcher, 1989). A shortcoming of the existing model was the treatment in the ichthyoplankton transport and fate model of pelagic eggs and larvae as passive drifters, subject to local horizontal currents averaged over the top 10 m of the water column. The vertical distribution of ichthyoplankton in the water column, however, is known to be variable and frequently related to hydrographic features (Buckley and Lough, 1987).

Ichthyoplankton may not be passive with respect to vertically averaged current fields. Some species are known to have persistent concentrations in areas where average horizontal currents are strong (e.g., Georges Bank herring (Iles and Sinclair, 1982)). Given the extensive data base on spatial and temporal distribution of pelagic ichthyoplankton that currently exists, empirical distributions of ichthyoplankton could now be employed in oil spill assessment models instead of relying on model-predicted transport of planktonic stages. In areas where data are lacking, field collections could be used to verify model predictions. Species-specific" and stage-specific assessments of the risks associated with OCS activities have not been well characterized, especially the risks associated with chronic discharges..

The population submodel assumes a compensatory spawner-recruit function, although there are no empirical data to support this assumption (Fletcher, 1989). If the assumption is invalid, then the effects of an oil spill on fish recruitment will be underestimated. Commercially exploited fishery resources of Georges Bank have declined during recent years (NMFS, 1989), presumably because of the effects of overfishing, and stocks may not be able to compensate for additional mortality associated with an oil spill.

POTENTIAL IMPACTS OF OCS ACTIVITIES

Georges Bank is one of the best-studied marine ecosystems in the world (Backus, 1987b). The dependence of biological features on the complex physical dynamics of Georges Bank makes it difficult, however, to predict the impacts of oil and gas development. DFO (1988) suggested that several unique environmental features of the bank make it more vulnerable to OCS impacts-especially oil spills-than other continental shelf habitats.

The central bank is shallow and well mixed vertically throughout the year. Oil spilled there would be distributed rapidly throughout the water column by physical mixing, increasing the potential exposure of both pelagic and benthic organisms. Following the spill from the *Argo Merchant in* 1976, concentrations as high as 210 micrograms/liter (ppb) of total hydrocarbons were measured to a depth of 20 m (Vandermeulen, 1982). Although the highest concentrations persisted for less than 2 weeks, concentrations elevated above background (1-50 ug/1) (ppb) were evident up to 5 months after the spill and were uniformly distributed throughout the water column (Boehm et al., 1978; Howarth, 1987; Farrington and Boehm, 1987). In the more stratified areas of the bank, less oil would reach deeper water.

Surface convergence zones have been observed on Georges Bank at the shelf break and in summertime tidal fronts. These zones are important concentrators of plankton, including the eggs, larvae, and juveniles of fishes and invertebrates. Correspondingly there is an abundance of plankton predators such as whales, fish, and sea birds and, consequently, high fishing activity (Harris, 1986). Surface convergence zones could also accumulate oil, increasing the exposure of both plankton and predators.

Any hydrocarbon resource on Georges Bank is much more likely to be gas than oil (U.S. DOI, 1988a). Therefore, oil spills or oil-well blowouts are less likely on Georges Bank than they might be in some other OCS areas. But a gas blowout could affect ecosystems, and pelagic organisms in particular. Gas condensate contains lower-molecular-weight hydrocarbons (e.g., benzenes and naphthalenes). Although they are highly toxic, they would be less persistent than compounds of higher molecular weight. Following the *Uniacke G-72* gas blowout near Sable Island, Nova Scotia, in February 1984, as much as 75 percent of the gas condensate was lost through evaporation during the first 24 hours. The rest formed a slick or became entrained in the water column. Elevated hydrocarbon concentrations of less than 100 micrograms/liter were detected in the upper 20 m of the water column (DFO, 1988). The severity of biological impacts from an oil or gas blowout or an oil spill would depend on its timing and the spatial extent of elevated hydrocarbons. For impact assessment, it is important to identify the timing and location of the use of spawning and nursery areas of important species.

Following a spill, weathering processes (e.g., evaporation, dissolution, and dispersion) and hydrodynamic features will strongly influence the fate of hydrocarbon contaminants. Low-molecular-weight hydrocarbons, although highly toxic, have relatively short half-lives and will not persist for long periods of time (Neff, 1989). Tidal currents on Georges Bank can disperse contaminants on the central bank rapidly and widely. Sedimented oil and other chronic discharges (e.g., drilling fluids and produced waters) would also be transported by tidal excursions and other hydrodynamic processes.

MMS's Georges Bank Monitoring Program examined the fate, transport, and effects of drilling fluid discharges from exploratory wells. The coarse fractions of drilling muds and cuttings remained in the immediate vicinities of the platforms. Finer fractions were transported downstream of the platforms and were rapidly dispersed. Using sedimentary barium concentrations as a chemical marker of the fate of drilling fluids, Neff et al. (1989) found elevated concentrations within 500 m of the platforms; beyond this range, barium concentrations were not distinguishable from background. No biological effects on benthic communities were attributed to these discharges.

Transport of fine particles (including contaminated ones) to submarine canyons during development and production might cause biological harm, especially if the particles accumulated in depositional areas. The ecological impacts of such discharges on the biological communities of the submarine canyons and their potential for trophic linkages *to* other parts of the Georges Bank ecosystem are unknown. Additional studies would be needed to assess the potential impacts of a gas blowout and transport of contaminated sediments-as well as other potential impacts—on submarine canyons.

Despite these concerns, there is sufficient information to provide the basis for assessment of the potential impacts of exploratory drilling on the Georges Bank ecosystem. Previous exploratory drilling revealed few or no consequences of drilling activities. However, neither long-term impacts associated with chronic discharges expected during development and production phases nor even acute impacts that may occur during a critical spawning window of any particular resource species are well understood. Site-specific studies during exploration will be required to characterize the spatial and temporal extent of chronic disturbances and to design appropriate restrictions for discharges during development and production.

SHORTCOMINGS OF THE DEIS FOR SALE 96

Although the panel's primary task was to assess the adequacy of available scientific information to support decisions on OCS activities, it also considered the reliability of the DEIS as a digest of the available information. In some areas (e.g., fisheries) the DEIS summarizes the information well. In others, the DEIS omitted important information or used it inappropriately. For example, information on the distribution of eggs and larvae of fish and invertebrates was not presented. For birds, the DEIS did 'not cite the most complete and current reports available at the time (e.g., Brown et al., 1975; Powers, 1983). It also failed to identify the three bird populations at special risk that are referred to above. There was no section on ecosystems. There was little consideration of the chronic effects of drilling and production discharges associated with oil or gas production and no consideration of the potential impacts of escaping gas or gas condensates.

MMS should be commended for trying to develop a quantitative model assessing the effects of an oil spill on fisheries resources. The specific model developed, however, assumed biological compensation that cannot be verified, and it considered only the effects of oil on pelagic eggs and larvae in the upper water column. It also assumed that eggs and larvae are passive drifters, which is not generally true. Additional serious shortcomings in the modeling are pointed out in Chapter 2.

CONCLUSIONS

The DEIS for lease sale 96 (Georges Bank) does not present an adequate description and evaluation of resources and potential impacts on them of OCS oil and gas activities. However, there is sufficient information available for an adequate description of the environmental features of the region and of the distribution and abundance of important biological resources. Despite important deficiencies in the DEIS's analyses of the sensitivity and recovery of populations and communities of organisms with respect to OCS-related activities, there is sufficient biological information on which to base a leasing decision.

More detailed site-specific analyses of ecological communities would be needed during exploration, and if commercial quantities of oil or gas reserves are discovered, additional information will be necessary to assess the site-specific environmental impacts of development and production. At present, there is not enough information on the vulnerability of local populations and communities to acute and chronic disturbances related to OCS development and production.

4

Socioeconomics

OVERVIEW

The panel concludes that considerable socioeconomic information exists that could be applied to the potential impacts of lease sale 96. Several of the socioeconomic studies conducted for Georges Bank address impacts related to space conflicts ashore and at sea, to demographic and economic changes, to spill and nonspill environmental impacts, and to onshore development and community infrastructure. Unfortunately much of this information is dated and no program has been established to acquire and incorporate information. Therefore, the panel believes that although extensive information is available, some of it is in the form of raw data, some was collected for other purposes, and some is out of date. MMS will have to update, collect, analyze, and synthesize the information before its adequacy can be evaluated for a leasing decision. Substantial additional site-specific and other information will be needed for decisions concerning OCS oil and gas development and production in the North Atlantic.

Socioeconomic impacts can result from activities during all stages of the OCS process, starting from the prelease stage and extending through decommissioning. The limited socioeconomic information presented by MMS has focused on those impacts resulting from development and production of OCS oil and gas. The socioeconomic effects that may occur before development and even before leasing have not been typically viewed by MMS as impacts of OCS activities. Nevertheless, some of these impacts are directly quantifiable, and all of them have real costs. With the exception of Alaska, no formal studies have addressed prelease and predevelopment impacts, either qualitatively or quantitatively. With regard to lease sale 96, a significant amount of information concerning early socioeconomic impacts could be obtained from public records, such as hearings. Nor have any studies been done that address the impacts of the decommissioning stage.

In the DEIS for lease sale 96, insufficient attention has been paid to previous experience. There was a lease sale in the North Atlantic (lease sale 42 in 1979), and eight exploratory wells were drilled. Other proposed sales in the region have led to EISS but were canceled. There is a great deal of experience with leasing, exploration, and development and production in the Gulf of Mexico and southern California. Leases have been sold elsewhere on the U.S. OCS. Unfortunately, MMS, which has not recognized the importance of predevelopment or even prelease socioeconomic impacts, has not taken full advantage of this experience to understand these socioeconomic impacts.

The OCS Lands Act Amendments of 1978 mandate consideration of impacts on the human environment in all decisions concerning the leasing and development of offshore tracts. The term “human environment” is defined by OCSLA to mean “the physical, social, and economic components, conditions, and factors which interactively determine the state, condition, and quality of living conditions, employment, and health of those affected, *directly or indirectly*, by activities occurring on the OCS . . ." (43 USC 1331(i) (emphasis added)). The panel notes that there is not only an unambiguous legal requirement for socioeconomic studies but also a need arising from the fact that OCS activities have had large effects on the human environment as described by OCSLA.

An accurate understanding of the socioeconomic implications of proposed OCS activity at the earliest stages of the leasing process is critical to the effective functioning of the OCS program in a period of difficult and often controversial decision making concerning national resource policy. Despite this clear mandate few data have been collected by MMS or anyone else that are specific to social and economic impacts of OCS activities. Over 95% of MMS's research has-been in ecology and physical oceanography. Although the practice of socioeconomic impact assessment has a relatively long history (Finsterbusch et al., 1983; Freudenburg, 1986), MMS has made little attempt to apply those techniques systematically or to do followup studies aimed at determining the degree to which socioeconomic assessments accurately predicted actual outcomes (Freudenburg, 1986; Seyfrit, 1988). Even the few socioeconomic data that have been collected were not collected in a systematic, scientific program or in concert with the scientific community.

As was stated in an earlier report of this committee (NRC, 1989a), the panel recognizes that the overall conclusion of this chapter, that socioeconomic impact analyses have been too narrowly construed to be useful in decision making, is not a criticism applicable only to the DOI, However, significant initiatives in this type of analysis have been made by some state and local governments (e.g., Hershman et al., 1988; Tri-County Socioeconomic Monitoring and Mitigation Program, 1988; Kasperson et al., 1989). Overall, socioeconomic studies must be based on an analytical framework, such as is outlined in this chapter. Further, appropriate data specific to the impacts of OCS activities must be gathered, as has been done for other disciplines. Socioeconomic impact studies should also be given higher priority than they have been, because OCS activities have had and will continue to have substantial socioeconomic impacts. In addition, socioeconomic impacts are the basis of much of the public opposition to the OCS leasing program. Detailed recommendations for the socioeconomic aspects of MMS's ESP will be provided in the panel's review of the ESP, scheduled for publication in 1991,

A FRAMEWORK FOR EVALUATING IMPACTS ON THE HUMAN ENVIRONMENT

Understanding and assessing impacts on socioeconomic systems (i.e., the "human environment" as specified in OCSLA) requires sociological, cultural, and political analyses. A framework for identifying relevant phenomena constituting socioeconomic systems was recently described by this committee (NRC, 1989a). The four elements of that framework were (1) the human environment, including potentiality affected systems; (2) activities that can produce impacts; (3) the dimensions of the potential impacts; and (4) the distribution of the impacts across human systems. These elements define the basic information requirements for socioeconomic impact assessment.

Activities That Can Produce Impacts

The activities associated with-OCS oil and gas can be conceptualized in five stages:

1. Prelease. Prelease activities include announcements of intention to lease, preparation of supporting documents (EISs and secretarial issue documents (SIDs)), and the lease sale itself. The impacts associated with these activities are anticipatory occurring in advance of any physical change to human, coastal, and marine environments. These impacts include community preparation to mitigate or exploit impacts, organization for opposition to development, community feelings of lack of autonomy and resulting outrage and alienation, and stress associated with uncertainty' about the future. These impacts can be amplified as the media carry news of them to wider publics and as groups and communities organize to prepare for OCS activity, or resist it through legal, political, or direct action.

2. Exploration. At the exploration stage, other types of impacts can begin to occur. Space-use conflicts can emerge in the sea, for dock space, for housing, for transportation routes, and so on. At this stage, economic and population growth associated with the project can begin. Finally, the onset of drilling introduces the possibility of spills.

3. Development. With development, the need for land-based support increases, as do employment and the purchasing of goods. At this stage, OCS activities have the potential for major transformation of the social and economic environments of the community (Grading and Freudenburg, 1989; a similar transformation (not OCS-related) was described by Bunker (1984)). Total direct and indirect employment resulting from U.S. OCS activities is large but is not reliably known.

4. Production. Production begins to shift OCS activities from the vicinity of the field itself to the areas of subsequent processing, transport, and use. Local communities experience drops in employment as support activities for drilling decline and as job skills learned for the extractive economy are less in demand. The potential for spills decreases or increases, depending on whether pipeline or tanker transportation of the product is chosen. Although pipelines are safer, they engender new space-use conflicts.

5. Decommissioning. Most impacts will cease with decommissioning, although some short-term population influx is associated with the process. Further, the alterations of the social and economic environment associated with an extractive economy will continue for an indeterminate time. To the extent that the socioeconomic systems have adapted to oil and gas activities, decommissioning can cause new stresses. Residents and capital (or investment) can move out of the area at the decommissioning phase or in the wake of a major spill.

Within a given region, these stages maybe occurring simultaneously for different projects.

Dimensions of Impacts

Impacts can be beneficial, adverse, or both at the same time. Commonly considered dimensions include the following

- Incidence: probability and uncertainty (how likely?). Many OCS impacts are uncertain, and so expected or "average" values of impacts are misleading. An adequate assessment of the impacts of OCS activities should, of course, include estimates of the more certain impacts of normal operations.
- Consequence: magnitude and severity (how much?). This is the most obvious dimension of impacts.

. Time and space (when where, how long, how big?). Question include whether impacts are continuous or periodic, how long they last, and when they occur (e.g., in the winter or the summer, during fish-spawning seasons, or during the tourist season)?

- Cumulative potential (how does it add to others?). Often impacts cannot be predicted by simply adding the activities that create them, because thresholds and indivisibilities can be encountered (e.g., one offshore support vessel could require additional dock space in a harbor, but 10 additional vessels could require a new harbor).
- Susceptibility to mitigation (can the damage be repaired?). Some impacts can be mitigated, but some, such as the destruction of a unique environment or way of life, cannot.
- Interactions. Each dimension can be considered alone, but they obviously interact and thus must be considered in that context.

Distribution of Impacts

Impacts are usually distributed unequally across various elements of the human environment (e.g., Gramling, 1980; Wolf, 1983; D ietz, 1987). The issue of who benefits and who bears the risk is important. Impacts of OCS activities are feh differentially by coastal and inland regions and by different social, cultural, and economic groups.

WHAT INFORMATION IS NEEDED

Assessment of the potential socioeconomic impacts of OCS activity differs from the assessment of ecological and physical oceanographic impacts in that significant socioeconomic impacts can occur *before* a lease sale. On the other hand, socioeconomic impact assessment is similar to the assessment of physical oceanography ic and ecological impacts in that additional site-specific information should be obtained before development and production decisions are made. Socioeconomic impact assessment is also like the assessment of other impacts in that one "of the best sources of insight is experience gained fro-m earlier activities, such as leasing in the North Atlantic and elsewhere, and development and production in the Gulf of Mexico and southern California. The information must be applicable to an assessment of the potential and actual impacts of OCS activities (i.e., in addition to any general or secondary information used, information is needed on the impacts of OCS activities). It should be based, as much as possible, on experience. The framework presented above provides guidance for organizing the information needed to assess impacts at each stage of the process.

Prelease and Lease Impacts

Before leasing, some information is required on the potential socioeconomic impacts of development and production so that the benefits and costs of the proposed action can be broadly weighed. More detailed information is required on prelease and exploration impacts. For prelease impacts, this need includes the communities' perceptions of risk; the communities' feelings of lack of autonomy and the extent to which their perceived 1oss of control leads to alienation and outrage; the extent to which the communities organize and prepare to oppose, mitigate, or exploit the effects of OCS activities; and the amount of stress associated with uncertainty in the community. These impacts are evi dent as a result of proposed and actual leases in the area, including lease sale 96. The research strategies to assess them are described primarily in the literature of risk perception, social change, construction of social problems, and psychological stress.

Within this category of impacts major obstacles have been encountered by the OCS leasing program, which range from organized letter writing campaigns through organized political opposition to threatened violence. Organized political opposition to the OCS leasing program has produced local, state, and federal legislation, including moratoria on exploration and production. A more systematic review and presentation of these local prelease impacts can better inform the decision making process.

Exploration Impacts

In addition to the above, information on impacts of exploration should address space use conflicts, both offshore and onshore; demographic and economic changes associated with exploration; impacts on community infrastructure; and the potential impacts of oil spills.

Impacts of Development, Production, and Decommissioning

In addition to information needed on prelease and exploration impacts, information should be gathered on the impacts of development, production, and decommissioning. It will be possible to obtain more site-specific information after exploration; the need to do so heightens the need to collect data specifically related to the potential impacts of the proposed activity. The assessment should consider all five stages of the OCS process (i.e., prelease through decommissioning) and should cover the dimensions of the potential impacts adequately. The information should permit identification of the relevant activities, communities, and groups that will be affected.

EVALUATION OF INFORMATION FOR SALE 96

The following list of studies and reports, with brief accompanying descriptions, indicates that most of the studies—even those funded by MMS-were not directly applicable to understanding predicting, and managing the socioeconomic impacts of OCS activities. Non-MMS studies for the most part have not been cited in the DEIS.

MMS's Environments! Studies Program

MMS responds to OCSLA's legal mandate to provide information to predict, assess, and manage the impacts of OCS activity (Section 20) through its Environmental Studies Program. Studies listed by MMS as social and economic received $1,933,413, which amounts to 2 percent of the $92 million spent by the Atlantic OCS region's ESP, from 1973 through 1988 (U.S. DOI, 1989). The studies described in that report include the following

1. *A Socio-Economic and Environmental Inventory of the North Atlantic Region* (TRIGOM, 1974). This study is a compilation of literature concerning a large number of physical and biological issues as well as demography, recreation, transportation, fisheries, and

canal and water use. Its stated objectives include use in preparing environmental impact assessments and identification of data gaps to guide research. The study is cited in the lease sale 96 DEIS.

2. *Environmental Consequences of Onshore Activity Resulting from Offshore Oil and Gas Development in New England* (Kramer and Watson, 1976). The study was intended to "determine the onshore environmental impacts of changes in economic activity resulting from offshore oil development on the New England Coast, and in the Mid-Atlantic." It found that OCS development in New England would cause serious local pollution problems in New Jersey as a result of oil refinery activity there. Nonpoint water pollution was identified as potentially important but was not analyzed. The study is not cited in the DEIS.

3. *A Summary and Analysis of Cultural Resource Information on the Continental Shelf from the Bay of Fundy to Cape Hatteras* (Moir et al., 1979). The study identified potential shipwreck sites of archaeological value, The study is cited in the DEIS.

4. *Assessing the Impact of Oil Spills on a Commercial Fishery* (University of Rhode Island (URI) and Applied Science Associates, Inc. (ASA), 1982). This study, at $954,068, is the most expensive "socioeconomic" study in the list, but it consisted mostly of physical and biological oceanography. It "utilized and further developed the ASA/URI Oil Spill-Fishery Impact Assessment Model System." Estimates of economic impacts were based on predictions of biomass decline in the ecological model. Bockstael (1989) pointed out that this approach failed to consider social factors, such as a fisherma n's ability to adapt to the impacts of large spills. Such responses could include fishing in different areas or fishing for different species. The study is cited in the DEIS.

5. *Travel Economic impact Model* (U.S. Travel Data Center, 1975). This study developed the Economic Impact Model to estimate "the annual impact of travel activity of U.S. residents on national, state, and county economies in this country." A second volume of this study used the model to assess impacts. of OCS development on "pleasure travel," but no conclusions relevant to the OCS were mentioned in the summary. The study is not cited in the DEIS.

6. *Assessment of Space and Use Conflicts Between the Fishing and Oil Industries* (Centaur Associates, Inc., 1981). The study consisted of literature review, modeling, and "site visits to 30 ports" all around the United States. It identified conflicts between the fishing and oil industries based on the identification of fishing gear and oil technologies and the history of interactions between the two industries in the Gulf of Mexico, southern California, and the North Sea. These conflicts included competition for labor, port space, repair facilities, financing, fuel, equipment, and supplies. It also identified potential mitigating measures and their costs. A model was developed to estimate the loss of catch to commercial and sport fishermen and its value. Finally,. the study projected the needs of the oil and fishing industries and the impacts of OCS development on the fishing industry for all areas of the continental United States except Alaska and the North Pacific. The study concluded that conflicts with oil structures are most likely to occur with otter trawls, bottom dredges, and purse seines. Structure-related debris was expected to present the greatest problem. The study was the basis for related sections in the DEIS, although it is not specific to the North Atlantic region.

7. Study *of Alternative Modes for Transporting OCS-Produced Oil and Natural Gas* (Policy Planning and Evaluation, Inc., 1983). The "study was based on a detailed literature search and extensive interviews with industry representatives." This study identified and compared the technical fusibility, regulatory framework, environmental constraints, and costs of alternative methods of transporting OCS oil and gas, including the associated onshore and offshore facilities that would be required. It is not specific to the North Atlantic, and it is not cited in the DEIS.

In addition to the above studies and the DEIS for sale 96, MMS produced EISS for earlier sales; the latest was the final EIS for sale 82, which was later canceled (U.S. DOI, 1984). For the most part, the information in previous EISs is incorporated into the most recent one either by description or by reference.

In general, the studies listed above did not address the specific impacts of OCS oil and gas development and were not specific to the North Atlantic region. Most of them need updating, because they were completed 10 or more years ago. The largest study on the economic costs from oil spills to commercial fishing, accounting for nearly half the "socioeconomic" studies budget, is a physical and biological study with socioeconomic implications but no socioeconomic analysis. Only the Centaur Associates study of space-use conflicts between the fishing and oil industries and the Policy Planning and Evaluation study of alternative modes for transporting OCS-produced oil and gas addressed the potential socioeconomic impacts of OCS development, although neither is specific to the North Atlantic region.

Non-MMS Sources of Information

This section summarizes some non-MMS information on potential socioeconomic impacts of oil and gas activities on Georges Bank. The universe of information is large, and no single source identifies all studies of potential OCS socioeconomic impacts. Therefore, the committee has not attempted here to provide an exhaustive review of all available literature, Instead, it has identified and summarized studies that cover each type of impact discussed above. Only one of them was cited in the DEIS.

1. *External Costs of Coastal Beach Pollution: A Hedonic Approach* (Wilman, 1985). A version of the OSRA model and a hedonic model were combined to calculate the expected recreational and economic impacts to Cape Cod beaches of hypothetical oil spills on Georges Bank.

2. *The Georges Bank Petroleum Study* (MIT, 1973). This NOAA-sponsored study examined the economic and environmental implications of alternative scenarios for development of oil on Georges Bank. The economic analysis was limited to examining changes in regional income due to oil industry transactions under alternative scenarios and did not consider environmental impacts. It also examined changes in regional water and air quality and the resultant effects on biota. No attempt was made to determine the socioeconomic impacts of these biological effects.

3. OCS *Oil* and Gas: *An Environmental Assessment* (Council on Environmental Quality, 1974). The study examined offshore environmental effects of OCS development and economic, social, and environmental impacts of associated onshore development.

4. *Managing* Our *Georges Bank Resources* (University of Rhode Island, 1979). This proceedings of a National Academy of Sciences regional forum concluded that impacts cannot be predicted very well. It was agreed that cleanup apparatus and trained personnel should be available locally and that a regional focus is needed to ensure that the long-term costs and benefits for New England are considered. Major concerns were the offshore interactions of the fishing and petroleum industries and major oil spills. A serious problem was the lack of trust in the governmental process and between the fishing and oil industries.

5. *Onshore Facilities Related to Offshore Oil and Gas Development: Estimates for New England (New* England River Basins Commission, 1976). The study examined the implications of OCS development by investigating onshore facilities and resultant impacts that might be

expected in New England from three sizes of oil and gas discoveries on Georges Bank. Sections included scenario development and estimation of the amounts of offshore activity necessary to produce resources from each size find. The study is cited in the DEIS.

6. *Effects on Commercial Fishing of Petroleum Development off the Northeastern United States* (Woods Hole Oceanographic Institution, 1976). The report considered the effects of OCS petroleum development on fisheries in three general categories: offshore interactions, onshore interactions, and pollution effects. Estimates were made of the potential magnitude of the effects on commercial fishermen. Recommendations were made as to steps that should be taken by the industries and by government to minimize undesired consequences.

7. *Offshore Petroleum and New England* (Grigalunas, 1975). The study examined and estimated the direct and secondary economic impacts on New England of alternative potential offshore oil and gas developments and possible petroleum refinery activity within the region under alternative scenarios.

8. *Effects on New England of Petroleum-Related Industrial Development* (Arthur D. Little, Inc., 1975). This was an extensive study of engineering, economic, and environmental factors associated with petroleum refining, pet rochem ical production, crude oil terminals and storage, and offshore oil and gas exploration and production on Georges Bank.

9. *Fishing and Petroleum Interactions on Georges Bank* (New England Regional Commission, 1977). The study assessed the available information on the Georges Bank environment and fisheries. It discussed the importance of sport fisheries in terms of participation, catch, expenditures, and "economic value," based on an estimate of user-day value. It concluded that much of the potential conflict between the fishing and oil industries could be mitigated by proper advance planning.

10. *Georges Bank* (Backus, 1987b). The Backus volume on Georges Bank is perhaps as complete a scientific assembly of knowledge as one will ever encounter on a single offshore drill site. It is a tour de force in several respects, but not in its coverage of socioeconomic concerns related to Georges Bank.

The concluding part of the book, "Conflicting Uses," provides a clear historical and legal exposition of lease sale 42 in 1979. Many of the prelease impacts emphasized in the present report were evident then. For example, the roles of a private environmental group, the Conservation Law Foundation of New England, and the Commonwealth of Massachusetts were considerable well before, during, and long after the lease sale. The relevance of prior socioeconomic analyses done by both the New England River Basins Commission and the New England Regional Commission (noted above) was also noted several times by different contributors to the "Conflicting Uses" section.

11. *A Review of Fisheries Resources and their Exploitation in the Gulf of Maine/Georges Bank Area in Anticipation of Hydrocarbon Exploration Activities* (DFO,1986). *This* document provides an overview of distributions, importance, and use of Georges Bank fisheries resources as well as their relationship to the biological and physical processes that sustain them. It also describes some of the regulatory measures designed for conservation purposes, distribution of fishing effort, environmental effects of fishing, and socioeconomic importance based on catch statistics and economic profiles of selected fishing communities in southwestern Nova Scotia. The data are intended for use in the analyses of dynamic social and economic factors and for consideration of hydrocarbon exploration activities might affect employment and income from the fishery so that the significance of possible disruptions can be weighed against economic and social values of the fishery. The document does not present that analysis, although employment "multiplier-figures are estimated.

12. ***Delimitation of** the Maritime **Boundary in the** Gulf **of** Maine **Area: Memorial** Submitted **by Canada*** (International Court of Justice, 1982). This document describes the pervasiveness of southwestern Nova Scotia's fishing industry, which is dispersed throughout hundreds of coastal communities that depend on it; its character; where it is concentrated; and its evolution. There are also descriptions of other dependent industries, indirect effects of disrupting the fishery and the broader impact that disruption would have on the total economy of the region and province, and a comparison with the U.S. fishery.

The memorial takes the position that unless hydrocarbon resources are developed by Canada, Canadian fishermen would be exposed to a risk for which no commensurate benefits would accrue to Canada if there were development in the United States. A survey is cited showing that few people in the offshore oil industry in the North Sea had previously been fishermen. In the North Sea there has been a decline in the fishing industry and a rise in offshore activities. The survey is cited to show that the offshore oil industry could not replace jobs lost in the fishing industry if access to Georges Bank were lost. Canada also maintained that an oil spill in any part of Georges Bank would be more likely to affect the Canadian than the United States shoreline.

Other non-MMS sources of information include transcripts of hearings, testimony comments on DEISs, and newspaper accounts.

Information Presented in the DEIS

The DEIS for sale 96 contains a section that describes the socioeconomic environment (pp. 111-104 to 111-149) and a section that describes impacts on it (pp. W-104 to IV-126). The socioeconomic environment is described very broadly in terms of demographic and employment data for 45 coastal counties from Maine to New Jersey. The information includes estimated population for 1985, estimated population change (1980- 1985), area, density, labor force, employment, unemployment, and per capita income for January 1987. A section on coastal land uses presents brief (one-paragraph) histories and overviews of the coastal zone management plans for the affected states. Information on recreation and tourism is limited to visitation data at National Park Service areas for 1985. All of this information is too limited in scope and detail to be of much value in impact assessment.

The major emphasis is on fisheries, many of which are currently depleted (NMFS, 1989). The basic discussion is about fish, not people. Twenty key commercial species are identified, and 12 are discussed in detail. Landing values and overall status of each species are presented, based on NMFS data. Commercial fishing is mentioned as the basis for a way of life.

The data presented are either much too general or inappropriate and do not allow for distinguishing impacts specific to OCS activity. The DEIS fails to consider many aspects of the human environment. It does not consider, for example, the distribution of the expected costs and benefits of OCS development to the economic, social, and governmental sectors. It also fails to consider such factors as values and way of life, risk perceptions, fear, uncertainty, anger, alienation, expectations of affected groups, and the degree of political organization resulting from the anticipatory nature of such impacts. Overall, the section is merely a compilation of secondary data, most of which are not appropriate for the purpose.

In the projection of impacts, the base-case scenario is that oil and gas will not be found in quantities sufficient to develop as a result of the current lease sale alone; instead, other finds from other sales will be needed for the reserves to be economically viable. There is an 'optimistic, high case," which assumes the discovery of enough oil and gas to be economically recoverable. Some moderate cumulative impacts are projected as a result of this and future lease sales. A support base is planned for Rhode Island. Impacts on local infrastructure are assumed to be low and confined to Washington County, Rhode Island.

The DEIS asserts that coastal recreation and tourism are key elements of the socioeconomic structure of the region. Impacts are expected to be negligible, based on the estimated low probability of a spill. Economic impacts of a potential spill are regarded as difficult to assess because of unpredictable variables including location, spill size, duration, oil composition, season, cleanup capability, and amount of publicity surrounding the incident. A "worst case" is presented as a spill occurring just before or during the summer season, because of the impact on beach use and tourist revenues, but this is not regarded as significant because it would merely shift the location of use patterns. This treatment is inadequate in two respects: it trivializes the economic impact by failing to disaggregate the burdens and benefits regionally, and it ignores the social dimension of spill impacts. Impacts and benefits are local. Thus, even if a loss of tourism in one area were made up by an increase in another, an appropriate economic analysis should consider the two as separate events (a loss and a benefit), not, as the DEIS does, merely cancel them out. In addition, there are noneconomic (social) values that would be affected by an oil spill (some of which could have economic aspects). These include behavior patterns, perceptions of risk, perceptions of environmental quality and well-being, etc.

An analysis of a potential spill on Long Island is cited that considers only the direct expenditure loss to the recreation industry and excludes cleanup costs, changes in waterfront property values and in tax revenues, and impacts on the aesthetic value of the recreational experience and the quality of life of visitors and residents. Visual impacts are not expected because OCS activities would be more than 50 miles from shore.

The greatest impact is expected on commercial fisheries, but this is regarded as minimal ~~because of the extremely small probability of a large oil spill~~ and the small effects of a small spill. Again, the impact is minimized by focusing on the small value of the expected economic consequences instead of on people's actions (i.e., the social dimension) based on their perception of high risk.

Fisheries impacts are grouped in three categories: spatial conflicts in dock and repair yards and in fishing locations, damage to fishing gear, and damage to fish. The DEIS treats spatial conflicts with trawlers as insignificant because of their predicted short duration and because of the small amount of space preempted by platforms. Mitigating measures are discussed that would help to alleviate and minimize damage to fishing gear. The DEIS calculates damage to fish by using a "catch 10SS" model. The most damage would be to species of limited mobility including lobster and scallops, Impacts of drilling discharges are also regarded as low., on the basis of the NRC's (1983) report, *Drilling Discharges in the Marine Environment,* the results of the Georges Bank Monitoring Study, the short duration, and the expected quick dispersion.

Moderate impacts are expected to commercial fisheries as a result of cumulative activities. Cumulative impacts considered include overfishing, loss of fishing grounds with the reorientation of the Exclusive Economic Zone border with Canada, Canadian oil and gas exploration along the international border, risk of spills from tankers, and future lease sales. Again, the impacts are expected to be low because of the greater probability of discovering gas than oil, low resource estimates, and the large amount of oil needed to affect fish stocks. These impacts are seen as indistinguishable from natural variation or localized near the wells.

In concision, the panel finds that the DEIS discusses economic impacts only in a limited way and ignores other social impacts. Although a broader range of information pertaining to social and economic impacts exists, it has not been analyzed and synthesized in the DEIS.

CONCLUSIONS

Predevelopment and prelease impacts have not been typically viewed as impacts of OCS activities. Nevertheless, some of these impacts are directly quantifiable, and all of them have real costs. With the exception of Alaska, no formal studies funded by MMS have addressed prelease impacts, either qualitatively or quantitatively. A significant amount of information can be obtained from public records, such as hearings. Several of the relevant studies address impacts related to space conflicts ashore and at sea, demographic and economic changes, spill and nonspill environmental impacts, and onshore development and community infrastructure. Unfortunately much of this information is dated.

In the DEIS for lease sale 96, insufficient attention has been paid to previous experience. There has been a lease sale in the North Atlantic (sale 42 in 1979), and eight exploratory wells were drilled. Other proposed sales in the region have led to EISS but were canceled. There is a great deal of experience with leasing, expiration, and development and production in the Gulf of Mexico and southern California. Leases have been sold elsewhere in the US. OCS. Unfortunately, except for the Alaska region, MMS has not taken full advantage of that experience to understand the socioeconomic impacts of OCS oil and gas activities throughout all stages of the process.

Although a study funded by the Alaska regional office addressed prelease impacts (Kruse et al., 1983), it has not been applied to the North Atlantic or other regions. Kruse et al. examined Inupiat perceptions of the potential effects of oil development on Alaska's North Slope and concluded that intense and widespread fears of potential impacts are themselves an impact on the community and that the ineffectiveness of Inupiat institutions in controlling offshore activities is a significant source of stress. Another study (Habitat North, Inc., 1979) funded by the Alaska region drew on previous experience by examining socioeconomic impacts of offshore oil and gas activity in Scotland, but its conclusions also have not found their way to other regions.

The panel concludes that considerable socioeconomic information exists that could be applied to the potential impacts of lease sale 96. Previous proposed sales in the North Atlantic and lease sale 96 have generated debate. However, the information has not been synthesized or analyzed by MMS, which has not recognized the importance of predevelopment and even prelease socioeconomic impacts. Therefore, the panel believes that although extensive information is available, MMS will have to update, collect, synthesize, and analyze the information before its adequacy can be evaluated for a *teasing* decision. Substantial additional site-specific and other information will be needed for decisions concerning OCS oil and gas *development* and *production in* the North Atlantic. And the socioeconomic impacts of *decommissioning*, which have received almost no attention, will also need to be considered.

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Appendices

Appendix A
Commission on Physical Sciences, Mathematics, and Resources

Norman Hackerman *(Chairman)*, Robert A. Welch Foundation, Houston
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Appendix B
Glossary

Advection. The process of transport of a fluid property or constituent by the mass motion of the fluid.

Anisotropy. The characteristic of a substance, for which a physical property, such as index of refraction, varies in value with the direction in or along which the measurement is made.

Baroclinic flow. The portion of the flow due to the additional horizontal pressure gradients resulting from density variations (as opposed to the portion caused by the slope of the free surface).

Barotropic. Refers to flow fields that are not affected by the density stratification.

Bathymetry. Knowledge of sea-floor topography, often used as a synonym for sea-floor topography.

Bedload. Particles of sand, gravel, or soil carried by the natural flow of a stream on or immediately above its bed.

Circulation model. A physical oceanographic model that estimates the currents and mass distribution of water as a **function** of time and space.

CODE. Coastal Ocean Dynamics Experiment.

Convergence zones. Areas where currents come together.

Cotidal. A term for points where high water occurs at the same time. Hence ***cotidal lines, cotidal charts.***

CTM. Characteristic tracing model.

Dispersion. Of **waves:** their-spreading as opposed to their steepening; of oil: its transport from the sea surface into the water column primarily due to breaking wave activity and associated near-surface turbulence.

Downwelling. The downward movement of surface water, generally caused by converging currents or by increased density.

Dyne. The unit of force in the centimeter-gram-second system of units, equal to the force that imparts an acceleration of 1 cm/s^2 to a 1 gram mass.

Eddies. Organized horizontal structures that rotate either clockwise or counterclockwise. Gulf Stream rings are examples of eddies.

Ekman transport. The horizontal transport of mass by direct wind-driven currents in the upper few tens of meters of the ocean. In the northern hemisphere this transport is directed at 90° to the right of the wind stress vector.

ESP. Environmental Studies Program.

Eulerian. See ***Lagrangian.***

Filaments. Typically, narrow mesoscale ocean circulation features in the upper ocean that have temperature and/or density characteristics of nearby prominent features. For example, patches of water originating from the Gulf Stream are found inshore off the Carolinas.

FNOC. Fleet Numerical Oceanographic Center.

Fourier decomposition, The separation of an even, regular time series into its harmonic components.

Gulf Stream rings. The Gulf Stream sheds 10-20 strong eddies each year. These are called rings because they have a ring of strong currents (1-3 m/s) at a radius of 50-150 km. The eddies shed to the north of the Gulf Stream have warmer centers and the currents are clockwise (warm-core rings). The rings to the south have relatively cold centers and the currents are counter-clockwise. These rings usually propagate slowly westward and thus the warm-core rings eventually strike the continental shelf/slope region north of the Gulf Stream.

Internal waves. The up-and-down "movement of horizontal density surfaces. These features propagate horizontally and vertically in the ocean.

Isobath. A line connecting points of equal water depths.

Lagrangian. Refers to motion following a specific small parcel of fluid, oil, or buoy. The opposite is *Eulerian*, which refers to motion of fluid past a fried measuring point.

M_2 constituent. The principal lunar component of semidiurnal tides.

Markov process. Assumes that in a series of random events the probability of an occurrence of each event depends only on the immediately preceding event.

Mesoscale. In this report, circulation features on horizontal length scales of 5-100 km.

Microstructure. Small (1-20 cm) vertical variations in the oceanic temperature, salinity, or density stucture.

Mixed layer. The upper few tens of meters of the upper ocean, which have an almost uniform temperature. The depth at which the ocean temperature decreases by 0.2" C is a common definition of depth of the mixed layer.

MMS, Minerals Management Service of the U.S. Department of the Interior.

Navier-Stokes equations. The equations of motion for a viscous fluid.

NOAA. National Oceanic and Atmospheric Administration of the U.S. Department of Commerce.

NODC. NOAA's National Oceanographic Data Center.

OCSLA. Outer Continental Shelf Lands Act of 1953 (amended in 1978).

OSRA(M). Oil Spill Risk Analysis (Model).

Ppt. Parts per thousand.

Pycnocline. The vertical section in the vertical density profile where the density changes most rapidly with depth.

Rectification. Generation of time mean flows in an otherwise harmonic flow (i.e., tides) due to nonlinearities in the flow (convective accelerations, frictional dissipation, or violations of shallow water wave assumptions).

Rings. See *Gulf Stream* rings.

Rossby wave. A wave on a uniform current in a two-dimensional nondivergent fluid system, rotating with varying angular speed about the local vertical (beta plane); this is a special case of barotropic disturbance, conserving absolute vorticity; applied to atmospheric flow, it takes into account the variability of the Coriolis parmeter while assuming motion to be two-dimensional.

Shelf break. The position in the ocean where the rate of deepening abruptly changes. The inshore **region is** the continental shelf. The offshore region is the continental slope. The break usually occurs in depths of ***100-200*** m.

Stokes velocity. The Lagrangian net particle velocity associated with finite amplitude waves. It results in a mass transport in the direction of surface wave propagation.

Sverdrup. Transport of 1 x 10^6 m^3/s of water.

Synoptic scale. A meteorological term indicating the scale of eddies resolved on weather maps, which is on the order of 1,000 km.

Synoptic. Refers to the use of data obtained simultaneously over a wide area for the purpose of presenting a comprehensive and nearly instantaneous picture of the state of the atmosphere or ocean over a large area at a given time.

Thermocline. The vertical section in the vertical temperature profile where the temperature changes most rapidly with depth.

Transition probability matrix. A matrix giving the probabilities that a variable will change from each possible state to every other possible state. For wind speed and direction, such a matrix would give the probability that a wind of a given speed and direction would change to any other speed and direction in a particular time.

Upwelling. T'he vertical movement of ocean water toward the surface.

Wind stress. The tangential force per unit area due to the horizontal movement of the wind over the sea.

Vorticity. For a fluid flow, a vector equal to the curl of the velocity of flow. A measure of rotational velocity.

Wave train. A series of waves produced by the same disturbance.